

State-of-the-art of fast pyrolysis in IEA bioenergy member countries

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ABSTRACT

Fast pyrolysis of biomass is becoming increasingly important in some member countries of the International Energy Agency (IEA). Six countries have joined the IEA Task 34 of the Bioenergy Activity: Canada, Finland, Germany, Netherlands, UK, and USA. The National Task Leaders give an overview of the current activities in their countries both on research, pilot and demonstration level.

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1. Introduction

Biomass fuels and residues can be converted to more valuable energy forms via a number of processes including thermal, biological, and mechanical or physical processes. While biological processing is usually very selective and produces a small number of discrete products in high yield using biological catalysts, thermal conversion often gives multiple and often complex products, in very short reaction times with inorganic catalysts often used to improve the product quality or spectrum. Pyrolysis has been applied for thousands of years for charcoal production but it is only in the last 30 years that fast pyrolysis at moderate temperatures of around 500 °C and very short reaction times of up to 2 s has become of considerable interest. This is because the process directly gives high yields of liquids of up to 75 wt% which can be stored and transported, and used for energy and chemicals in a variety of applications [1]. Fig. 1 summarizes the processes and markets for the liquid product from fast pyrolysis.

2. Fast pyrolysis

In fast pyrolysis, biomass decomposes very quickly in the absence of oxygen to generate mostly vapors and aerosols and some charcoal and gas. After cooling and condensation, a dark brown homogenous mobile liquid is formed which has a heating value about half that of conventional fuel oil. A high yield of liquid is obtained with most biomass feeds low in ash. The essential features of a fast pyrolysis process for producing liquids are:

- Very high heating rates and very high heat transfer rates at the biomass particle reaction interface usually requiring a finely ground biomass feed of typically less than 3 mm as biomass generally has a low thermal conductivity.
- Carefully controlled pyrolysis reaction temperature of around 500 °C to maximize the liquid yield for most biomass.
- Short hot vapor residence times of typically less than 2 s to minimize secondary reactions.
- Rapid removal of product char to minimize cracking of vapors.
- Rapid cooling of the pyrolysis vapors to give the bio-oil product.

The main product, bio-oil, is obtained in yields of up to 75 wt% on a dry-feed basis, together with by-product char and gas which can be used within the process to provide the process heat requirements so there are no waste streams other than flue gas and ash. Liquid yield depends on biomass type, temperature,

hot vapor residence time, char separation, and biomass ash content, the last two having a catalytic effect on vapor cracking.

A fast pyrolysis process includes drying the feed to typically less than 10% water in order to minimize the water in the product liquid oil, grinding the feed to give sufficiently small particles to ensure rapid reaction, fast pyrolysis, rapid and efficient separation of solids (char), and rapid quenching and collection of the liquid product (often referred to as bio-oil). The basic fast pyrolysis process is depicted in Fig. 2.

2.1. Fast pyrolysis reactors

At the heart of a fast pyrolysis process is the reactor. Although it probably represents only about 10–15% of the total capital cost of an integrated system, most research and development has focused on developing and testing different reactor configurations on a variety of feedstocks, although increasing attention is now being paid to control and improvement of liquid quality and improvement of liquid collection systems. The rest of the fast pyrolysis process consists of biomass reception, storage and handling, biomass drying and grinding, product collection, storage and, when relevant, upgrading. Several comprehensive reviews of fast pyrolysis processes for liquids production are available such as [2–4]. A large number of organizations are active in research on fast pyrolysis [5]. The main technologies are bubbling fluid beds; circulating fluid beds and transported beds; the rotating cone which is a type of transported bed reactor; and ablative pyrolysis which are all described in [5]. The key requirements in the design and operation of a fast pyrolysis process are heat transfer and char removal as char and the ash are catalytically active [5].

2.2. Pyrolysis liquid—Bio-oil

Crude pyrolysis liquid or bio-oil is dark brown and approximates to biomass in elemental composition. It is composed of a very complex mixture of oxygenated hydrocarbons with an appreciable proportion of water from both the original moisture and reaction product. Solid char may also be present. Typical organics yields and their variation with temperature is shown in Fig. 3. Similar results are obtained for most biomass feedstocks, although the maximum yield can occur between 480 and 520 °C depending on feedstock. Grasses, for example, tend to give maximum liquid yields of around 55–60 wt% on a dry feed basis at the lower end of this temperature range, depending on the ash content of the grass.

The liquid is formed by rapidly quenching and thus ‘freezing’ the intermediate products of flash degradation of hemicellulose, cellulose and lignin. The liquid thus contains many reactive species, which contribute to its unusual attributes. Bio-oil can

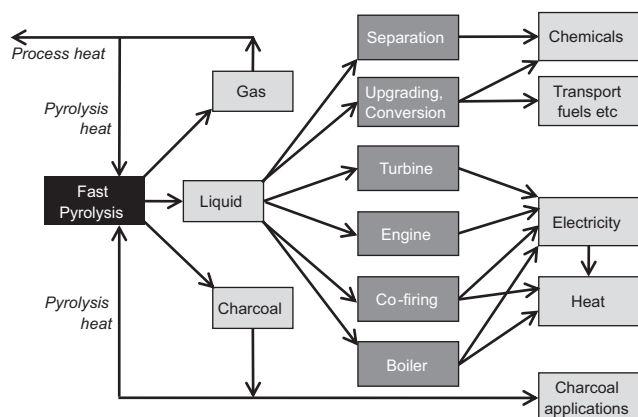


Fig. 1. Products from thermal biomass conversion.

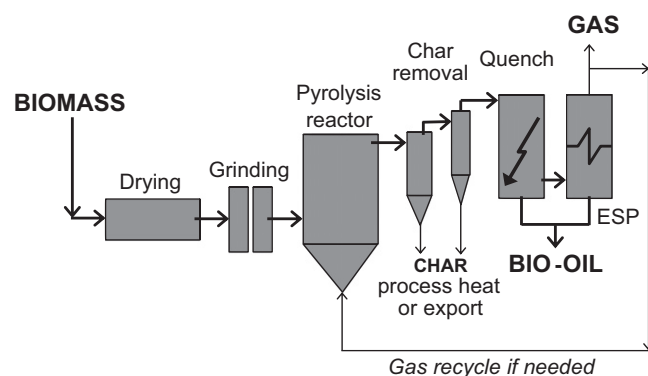


Fig. 2. Fast pyrolysis process.

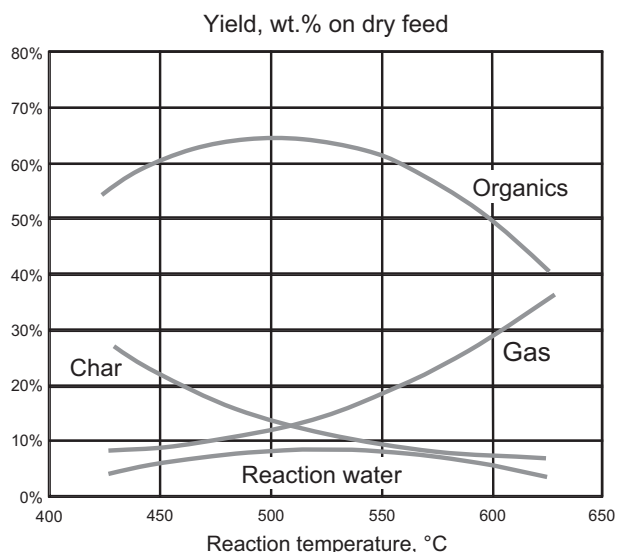


Fig. 3. Variation of products from Aspen Poplar with temperature.

Table 1
Typical properties of wood-derived crude bio-oil.

Physical property	Typical value
Water content	25%
pH	2.5
Specific gravity	1.2
Elemental analysis (on dry basis)	
C	56%
H	6%
O	38%
N	0–0.1%
HHV (as produced)	17 MJ/kg
Viscosity (20 °C and 25% water)	40–100 mPas
Solids (char)	0.1%
Vacuum distillation residue	up to 50%

be considered a micro-emulsion in which the continuous phase is an aqueous solution of holocellulose decomposition products, that stabilizes the discontinuous phase of pyrolytic lignin macro-molecules through mechanisms such as hydrogen bonding. Aging or instability is believed to result from a breakdown in this micro-emulsion.

2.3. Bio-oil characteristics

Fast pyrolysis liquid has a higher heating value of about 17 MJ/kg as produced with about 25 wt% water that cannot readily be separated. While the liquid is widely referred to as 'bio-oil', it will not mix with any hydrocarbon liquids. It is composed of a complex mixture of oxygenated compounds that provide both the potential and challenge for utilization. There are some important properties of this liquid that are summarized in Table 1. Pyrolysis oil typically is a dark brown, free-flowing liquid. Depending on the initial feedstock and the mode of fast pyrolysis, the color can be almost black through dark red-brown to dark green, being influenced by the presence of micro-carbon in the liquid and chemical composition. Hot vapor filtration gives a more translucent red-brown appearance owing to the absence of char. High nitrogen content can impart a dark green tinge to the liquid.

For any application, there are many particular characteristics of bio-oil that require consideration. These have been extensively reviewed [5,6]. The liquid contains varying quantities of water, which forms a stable single-phase mixture, ranging from about 15 wt% to an upper limit of about 30 wt% water, depending on the feed material, how it was produced and subsequently collected. A typical feed material specification is a maximum of 10% moisture in the dried feed material, as both this feed moisture and the water of reaction from pyrolysis, typically about 12% based on dry feed, both report to the liquid product. Pyrolysis liquids can tolerate the addition of some water, but there is a limit to the amount of water which can be added to the liquid before phase separation occurs, in other words the liquid cannot be dissolved in water. Water addition reduces viscosity, which is useful; reduces heating value, which means that more liquid is required to meet a given duty; and can improve stability. The effect of water is therefore complex and important. Bio-oil is miscible with polar solvents such as methanol, acetone, etc. but totally immiscible with petroleum-derived fuels. This is due to the high oxygen content of around 35–40 wt%, which is similar to that of biomass, and provides the chemical explanation of many of the characteristics reported. Removal of this oxygen by upgrading requires complex catalytic processes which are described below.

The density of the liquid is very high at around 1.2 kg/l, compared with light fuel oil at around 0.85 kg/l. This means that the liquid has about 42% of the energy content of fuel oil on a weight basis, but 61% on a volumetric basis. This has implications for the design and specification of equipment such as pumps and atomizers in boilers and engines. Viscosity is important in many fuel applications [7]. The viscosity of the bio-oil as produced can vary from as low as $25 \text{ m}^2 \text{ s}^{-1}$ to as high as $1000 \text{ m}^2 \text{ s}^{-1}$ (measured at 40 °C) or more depending on the feedstock, the water content of the bio-oil, the amount of light ends collected and the extent to which the oil has aged. Pyrolysis liquids cannot be completely vaporized once they have been recovered from the vapor phase. If the liquid is heated to 100 °C or more to try to remove water or distil off lighter fractions, it rapidly reacts and eventually produces a solid residue of around 50 wt% of the original liquid and some distillate containing volatile organic compounds and water. While bio-oil has been successfully stored for several years in normal storage conditions in polyolefin plastic drums without any deterioration that would prevent its use in any of the applications tested to date, it does change slowly with time, most noticeably there is a gradual increase in viscosity. More recent samples that have been distributed for testing have shown substantial improvements in consistency and stability, demonstrating the improvement in process design and control as the technology develops.

Aging is a well known phenomenon caused by continued slow secondary reactions in the liquid which manifests as an increase in viscosity with time. It can be reduced or controlled by the addition of alcohols such as ethanol or methanol. In extreme cases phase separation can occur. It is exacerbated or accelerated by the presence of fine char. This has been reviewed by Diebold [8,9].

2.4. Applications of bio-oil

Bio-oil can substitute for fuel oil or diesel in many static applications including boilers, furnaces, engines and turbines for electricity generation which was been thoroughly reviewed in 2004 [1] and many aspects have not changed very much. The most significant changes since then are:

An appreciation of the potential for fast pyrolysis to be a pretreatment method i.e., for bio-oil to be an effective energy carrier

- Greater interest in bio-oil as a precursor for second generation biofuels for transport.

- Greater awareness of the potential for fast pyrolysis and bio-oil to offer more versatile process routes to a wider range of products and contribute to biorefinery concept development.
- Considerably greater interest in upgrading bio-oil sufficiently for it to be used for heat, power and other applications with greater confidence by users.

3. UK

3.1. Research activities

3.1.1. Aston University Bioenergy Research Group (BERG)

The Bioenergy Research Group has been working on fast pyrolysis of biomass for over 25 years and has evolved as a leading academic research group in this area with regular reviews on pyrolysis [5,10,11] and bio-oil upgrading [6,12]. The focus of the work is on applied research into all aspects of the fast pyrolysis processing chain that starts with biomass preparation and pretreatment such as washing for ash management [13] and effect of growing conditions [14,15], fast pyrolysis in fluid bed and ablative pyrolysis reactors from 100 g/h to 5 kg/h [16] where there has been significant developments in CFD modeling [17–23]; management of secondary catalytic and thermal decomposition reactions; and design and development of liquid collection hot vapour filtration [24] and quench and electrostatic precipitators. Attention has recently focused on upgrading opportunities and requirements that cover all aspects of physically, chemically and catalytically upgrading bio-oils [6,12]. In support of this research is a comprehensive suite of characterisation methods that includes TGA, GPC, Py-GC/MS/FID with the possibility of including a secondary reactor in the Pyroprobe unit for catalyst screening [14,25–27].

For applications, a comprehensive review was published in 2004 [1] which is invariably one of the most cited publications in fast pyrolysis on Google. Applications of fast pyrolysis that have been researched include production of slow release fertilisers by nitrogenolysis [28] and catalytic pyrolysis for improved product quality [29]. Lignin processing has been the subject of recent research [30–33]. There has been a continuous interest in techno-economic assessment [34,35] which has sometimes been combined with process modeling [36–38].

3.1.2. Aston University European Bioenergy Research Institute

The recently created European Bioenergy Research Institute (EBRI) at Aston University, was established to carry out advanced research and knowledge transfer in many aspects of bioenergy with a new purpose build laboratory to open early in 2013. In addition to the fast pyrolysis work of BERG, intermediate pyrolysis is a key technology in EBRI, with a novel intermediate pyrolysis technology for production of gases, fractionated liquids for use in engines and solids for use as biochar. There are demonstration facilities for several technologies, including a 200 kg/h intermediate pyrolyser, to provide industrial research collaborators with opportunities to run process trials, evaluate feed materials, and study combinations of processes prior to investment. EBRI is collaborating with Severn Trent Water to convert sewage sludge into heat and power; with Johnson Matthey to develop catalyst-based tar reforming units; and with IIT Delhi, IIT Ropar and IISc Bangalore in the field of practical bioenergy solutions for rural areas. Our key research interests are:

- Application of aqueous pyrolysis fractions for anaerobic digestion.
- Closing of the fertilizer cycle for algae cultivation via intermediate pyrolysis of algae and extraction of biochar.

- Separation of hydrogen from reformed intermediate pyrolysis vapors.
- Direct use of intermediate pyrolysis bio-oil/biodiesel mixtures in engines (using rape and sewage sludge as feedstock).
- Micro kinetic studies for the evaluation of kinetic parameters of lignin degradation and tar formation.
- Catalytic conversion of intermediate pyrolysis products.

3.1.3. University of Leeds

Biomass pyrolysis research includes: fundamental studies of the impact of inorganics and metals in thermal conversion of biomass [39,40]; optimization of fuel quality and yield of energy crops; alternative biomass resources including marine biomass and waste; biomass pretreatment to improve fuel properties for various conversion processes, in particular: torrefaction; soot characterization and understanding the mechanism of PAH and soot formation; the nitrogen cycle in biomass production and the influence on nitrogen chemistry in thermal conversion; co-firing coal and biomass; novel steam reforming for the production of hydrogen from pyrolysis and vegetable oil [41]; and hydrogen from biomass and wastes by pyrolysis–gasification. Experimental work is complemented by theoretical studies using thermodynamic, kinetic, or molecular modeling software.

A range of bench scale and mini-pilot scale reactors for pyrolysis investigations of waste/biomass process parameters, including; continuous screw kiln pyrolysis–gasification reactor enabling first stage pyrolysis at 500 °C and second stage steam catalytic gasification at 800 °C. Fully instrumented with lab-view; 3 m long × 0.5 m diameter oil-fired furnace with full exhaust gas analytical suite for pyrolysis oil combustion studies. A wide range of advanced analytical equipment for fuel and product characterization including; pyrolysis-gas chromatography-mass spectrometry of biomass; gas chromatography-atomic emission spectrometry; thermogravimetric analysis-mass spectrometry; inductively coupled plasma-mass spectrometry; thermogravimetric analysis-Fourier transform infra-red spectrometry; size exclusion chromatography; and a full suite of fuel testing equipment.

A wide range of advanced analytical equipment for fuel and product characterization including; pyrolysis-gas chromatography-mass spectrometry of biomass; gas chromatography-atomic emission spectrometry; thermogravimetric analysis-mass spectrometry; inductively coupled plasma-mass spectrometry; thermogravimetric analysis-Fourier transform infra-red spectrometry; size exclusion chromatography; and a full suite of fuel testing equipment.

3.1.4. University of Nottingham

Activities at the University of Nottingham on pyrolysis and related topics cover the following:

- Torrefaction—impact of feedstock and pyrolysis conditions on the composition and combustion characteristics.
- Fluidized bed gasification.
- Hydrothermal treatment at elevated temperatures and pressures both for liquid fuel production and for artificial maturation to produce coal and carbon-like materials.
- Thermally mediated solvent extraction of biomass to produce liquid fuels and bitumen substitutes in high yield that are compatible with petroleum feedstocks, using both H-donor and non-H donor solvents. Hydrogen-donor solvents can give rise to selectivities of over 60% on a carbon basis to liquid products.
- In bed upgrading of fast pyrolysis oils with metals.

The research is supported by EPSRC – fluidised bed gasification and the Engineering Doctorate Centre on Efficient Fossil Energy Technologies that includes a number of projects on biomass – and by industry, that includes a BP project on thermally mediated solvent extraction.

3.1.5. Cranfield University

Prof. Sai Gu is leading a research team at Cranfield University in biomass thermo-chemical conversion. Their research covers computational modeling of pyrolysis, gasification and combustion, kinetic studies of biomass thermal decomposition, and assessment of feedstock and technology development in a global scale. A close partnership has been formed between the Cranfield group and the Aston University Bioenergy Research Group. Prof. Gu has been actively prompting advanced bioenergy technologies globally, currently being the PI of an EPSRC Collaborative Research Project in Energy with South Africa, the lead academic of a Leverhulme-Royal Society Africa Award 2009 with Ghana, and the coordinator of the EC FP7 ECOFUEL project with China. Other current activities include:

- Computational modeling of pyrolysis, gasification and combustion.
- Kinetic studies of biomass thermal decomposition.
- Assessment of bioenergy and biofuel potentials.

3.1.6. University of York

The University of York Green Chemistry Centre of Excellence promotes the application of green and sustainable technologies particularly those that can be used to deliver products that meet consumer and legislation requirements. The use of microwaves has been proven to selectively activate components of biomass leading to a much more controlled decomposition process than can normally be achieved. The outcome is a range of valuable products including pyrolysis liquids and biochar and chemicals from sustainable sources of carbon including waste materials. Microwave irradiation is rapid and volumetric with the whole material heated simultaneously thus allowing the processing of poor thermal conducting materials such as wood. Microwave heating can be controlled instantly and the power applied can be accurately regulated. This allows safe and precise control, even when applying very rapid heating rates. Furthermore, microwave pyrolysis occurs at lower temperatures whilst generating materials with higher calorific values. The team at the Green Chemistry Centre have proven this technology at scales from grams to tens of kilograms. In 2011, they will expand their facility into the Biorenewables Development Centre, a multifunctional space containing semi-scale equipment for microwave pyrolysis, supercritical CO₂ extraction, ammonia fiber expansion and fermentation alongside all the necessary pre-treatment apparatus.

3.2. Demonstration activities

3.2.1. Centre for process innovation

The Centre for Process Innovation (CPI) has cooperative research and development programme with Tata Steel which includes the establishment of a high temperature processing unit. This is currently equipped with a large batch pyrolyser and a flexible gasification system, with plans to expand the facilities to offer a wider range of integrated processing systems leading to bioenergy and biofuel applications. The facility offers demonstration scale processing of biomass derived products for energy and chemicals, Scale up and commercial assessment of new opportunities.

3.2.2. Biomass Engineering Ltd. (BEL)

BEL started work on preliminary process and conceptual design of its fast pyrolysis plant (FPP) as far back as 2006. Subsequent equipment specifications, detailed design, manufacture and procurement followed and today the original concept is being turned into reality. Initially, the plant is rated at 250 kg/h feedstock input and is designed to convert sawdust from clean wood into pyrolysis oil. Future design amendments will accommodate a program of trials on alternative potential fuels. At the heart of the process is a purpose built reactor vessel that utilizes fluidized bed technology to convert the feedstock into pyrolysis gases before quenching them to form pyrolysis oil. Both char and recycle gas byproducts are used to heat the fluidized bed of the reactor. Experimental analysis of the proposed initial feedstock has already been undertaken by Aston University on behalf of BEL using their 150 g/h and 1 kg/h pyrolysis rigs to establish conditions producing the highest organics yield. The results have been used to determine the optimum operating conditions for the FPP. The FPP will operate at BEL's purpose-built facility in Newton-le-Willows and is expected to be installed, commissioned and producing pyrolysis oil by the end of 2011/early 2012. A future program of works will also include experimentation on the pyrolysis oils produced by various feedstocks in order to determine their potential for use as raw fuel, fuel additive and chemical agent.

3.3. Commercial applications

3.3.1. 2G BioPOWER Ltd

G Biopower is a fledgling development company whose aim is development

- Advanced biofuels from municipal and commercial waste.
- Focus is on the use of pyrolysis and upgrading based on Envergent RTP™ (Rapid Thermal Processing) pyrolysis technology and upgrading via hydroconversion from UOP.
- Projects are currently under development in the South East and North East of England.

3.3.2. Conversion and Resource Evaluation (CARE) Ltd

Conversion and Resource Evaluation Ltd. provides a wide range of services in biomass pyrolysis including:

- Detailed chemical engineering and process design of biomass pyrolysis systems, all unit operations from feedstock handling to end use for power, heat, chemicals and products.
- Organization and evaluation of biomass and waste feedstock pyrolysis at laboratory, demonstration and commercial scale.
- Technology surveys, reviews and feasibility studies on pyrolysis.
- Due diligence of pyrolysis technologies.
- Techno-economic modeling and evaluation of complete pyrolysis systems from feedstock reception to end use of products (heat, power, combined heat and power and chemicals/products).
- Market evaluation of the opportunities for renewable products and technologies.
- Assistance with plant trouble-shooting, independent monitoring and evaluation, environmental legislation, process authorization and compliance with emissions.

Current activities in biomass pyrolysis:

- Design, build and commission a 50 kg/h slow pyrolysis reactor for char production with environmental compliance.

- Fast pyrolysis of biomass and wastes at 0.5, 1.5 and 250 kg/h for the production of liquids for subsequent upgrading to a blendate for liquid transport fuels; mass and energy balance modeling; techno-economic assessment of the production of the blendate from a 100,000 t/y input integrated biomass fast pyrolysis process.
- Refurbishment of a 5 kg/h fluid bed fast pyrolysis reactor system for the production of liquids for a UK university; component replacement and upgrading of control system.
- Pyrolysis of a high ash material for the recovery of metals from the char. Mass and energy balances and technology selection.
- Development of sensors for high temperature process monitoring; advice on gas contaminants during pyrolysis and gasification of biomass in a magnetic suspension balance and provision of advice on catalysts for gas cleaning and conditioning.

3.3.3. Future blends

Future Blends Ltd aims to develop low carbon, low-cost biofuels that can be integrated directly into the current fuel supply chain. The company was set up in 2010 to exploit the outcome of the Carbon Trust's Pyrolysis Challenge which was set up to develop a novel process to produce upgraded pyrolysis oils from waste biomass (such as municipal and wood waste) which can be blended with diesel at the point of distribution. Analysis of the Future Blends process has shown that it potentially offers the lowest cost production route of any biofuel technology of between £0.30 and £0.48 per liter. Further independent analysis has also shown that the carbon footprint of this new pyrolysis biofuel could achieve a carbon saving of 95% compared to conventional fossil fuels. This is significantly higher than some existing biofuels, which also do not currently factor in the impacts of land use change when calculating the carbon saving.

The technical development is focused in two specific areas:

- Pyrolysis: High conversion yields of bio-oil from low-value biomass.
- Upgrading: Novel methods of upgrading bio-oil to transport-grade fuel are being developed. These are potentially more cost-effective than the hydrogenation routes conventionally used for upgrading pyrolysis oil.

4. USA

4.1. Ranking of fast pyrolysis in the area of bioenergy

Since the 1980s and until recently pyrolysis of biomass has received limited recognition within the U.S. As late as the 2005 Multi-Year Program Plan (MYPP), the Department of Energy (DOE) Office of the Biomass Program (OBP) focused on gasification as the thermochemical biomass conversion route of interest. As of the 2007 MYPP, text describing pyrolysis as another option for thermochemical conversion was introduced. Over the past 3 years pyrolysis has become recognized as a key route for liquid fuels production from biomass. In the recent review of the DOE-OBP program [42], bio-oil is now identified with sugars as the two biomass conversion intermediates for liquid fuels production while gasification is de-emphasized.

4.2. Research activities

The key funding for research in biomass conversion by pyrolysis comes from the DOE-OBP with additional support from the Department of Agriculture (USDA) Agricultural Research Service (ARS). DOE-OBP funds most of its effort through competitive

solicitations with some directed research at the national laboratories. Similarly, USDA-ARS directly funds pyrolysis research at its Eastern Regional Research Center (ERRC) as well as some efforts through its national program involving some universities.

4.2.1. Bio-oil stabilization

A major effort has been undertaken by five groups in response to a solicitation by DOE on Stabilization of bio-oil. Much of the detail has not been published from this work, but presentations of the efforts were made at the Peer Review meeting and are posted on-line [43].

One effort at the University of Massachusetts-Amherst is led by Prof. George Huber. The stabilization work has focused on the use of microfiltration membrane [44] for char removal and catalytic processing for fuel production [45]. A recent development is the move of Prof. Huber to the University of Wisconsin during the summer of 2012.

At RTI International the stabilization effort has focused on catalytic pyrolysis. Results presented at the recent DOE platform review [46] show that with catalysts the bio-oil yield dropped from 48.0% in their system to 5.8–12.7% depending on the catalyst. There was also a large fraction of aqueous byproduct and coke deposit on the catalysts. The bio-oil oxygen content ranged from 34.3 down to 21.3 on the dry basis compared to the uncatalyzed baseline of 40.6% [47].

The Iowa State University group, led by Prof. Robert Brown, has three pathways under investigation [46] to improve stability of bio-oil:

- Reduce oxygen content of organic compounds.
- Remove carboxylic acid groups.
- Reduce charcoal content.

Their approaches include:

- Biomass pretreatment
 - Water washing, dilute acid washing, and acid infusion.
- Hot vapor filtering
 - Use a moving bed filter to remove fine char particles.
- Fractionating bio-oil recovery
 - Use a 5-stage bio-oil recovery system to produce distinctive fractions of oil and concentrate desirable compounds.
- Catalytic post-treatment
 - Develop heterogeneous catalysts capable of simultaneous hydrogenation and esterification of post-production bio-oil.
- Optimization and stability testing
 - Use laser diagnostics to optimize hot vapor filtration and bio-oil collection,
 - Use computational fluid dynamics to understand transport processes, and
 - Characterize bio-oil stability using appropriate testing methodology.

The UOP led group [46] included studies on catalytic pyrolysis at ERRC. As part of the project Pall designed a hot gas filtration system that was installed and tested at NREL. PNNL performed post pyrolysis processing tests to evaluate the usefulness of hydrothermal treatment and transfer hydrogenation as means to stabilize bio-oil. Ensyn performed process parameter tests and condensed product filtration tests. None of these results are yet published except for the on-line presentation, but a number of manuscripts are in process.

The group at Virginia Tech University, led by Foster Agblevor (recently moved to Utah State University) concentrated on catalytic pyrolysis as the means to produce a stable bio-oil.

Commercial catalysts were tested and product oil was further processed as a diluent in heavy gas oil in a catalytic cracker [48]. Their work included the development of a acid number analysis specifically for bio-oil measurements [49]. A related effort included the development of new hydrotreatment catalysts, which were tested with guaiacol as a model for bio-oil [50].

4.2.2. Bio-oil upgrading

A major new effort is being undertaken by four groups in response to a solicitation by DOE on upgrading of bio-oil. These 3-year projects are underway but there are no results available yet. The summaries of the projects suggest the new initiatives that DOE is undertaking in order to extend catalyst lifetime to at least 1000 h of continuous operation.

- PNNL in partnership with UOP will further investigate fixed-bed hydrotreating and attempt to unravel the coking mechanisms that have plagued this R&D.
- Grace in partnership with PNNL, VTT of Finland, and ORNL will be developing catalysts to use in an advanced catalyst bed configuration.
- Battelle in partnership with PNNL, SüdChemie and Marathon will be developing catalytic pyrolysis and catalytic hydrotreating optimized for use with catalytic pyrolysis.
- GTI will be scaling up their version of hydrothermal liquefaction, Integrated Hydrothermal Liquefaction and Hydroconversion. They report a fully integrated process of catalytic pyrolysis and catalytic hydrotreating with an overall reduced capital cost and no external hydrogen requirement [51].

4.2.3. National Advanced Biofuels Center (NABC)

Another effort undertaken by DOE is the NABC. Within NABC three relevant pyrolysis-based liquefaction concepts were being investigated as part of 6 options with the intent to develop at least one option to the point of readiness for demonstration by mid-2013. The three concepts have been under development since May 2010. They include:

- catalytic pyrolysis led by UOP with processing participation by ERRC, Albemarle, NREL, [51] (within this task PNNL has been evaluating chemical looping in an attempt to minimize hydrogen consumption [52].
- hydrothermal liquefaction (HTL) led by PNNL with participation of UOP in upgrading the bio-oil product [53]. NABC researchers obtained oil yields of 30 weight % (53% yield on a carbon basis) – the oil contains 10% oxygen on a dry basis – the low oxygen content correlates to an improvement in the total acid number (TAN) of the oil of 30 – the oil is thermally stable.

Pall provides process support in bio-oil separations while BP provides product assessment.

In a recent decision by the NABC management, as part of their down-select process, hydrothermal liquefaction and hydrothermal liquefaction have been selected for more basic research support, as unready to advance to pilot scale within the NABC structure. The catalytic pyrolysis effort transferred from the NABC and further development is being supported privately.

4.2.4. Core R&D

In addition, another significant DOE-funded effort is the Core Pyrolysis R&D project which is undertaken at PNNL and NREL

with a contribution from ORNL. Results of the project over the past two years were reviewed at the recent Platform review [53]. Important developments have been reported on the subjects of catalytic pyrolysis [53,54]; bio-oil neutralization and stabilization [55]; and techno-economic assessments of pyrolysis as a liquid transportation fuel production process [56] and as a means to supplement refinery input [57]. Bio-oil hydrotreating has been a major component of the DOE-funded program—including partial deoxygenation using a semi-batch reactor system [58,59]; model compound mechanistic studies, [60] which have led to issuance of two U.S. patents [61,62]; and continuous-flow reactor studies [63]. Other efforts involved international collaborations related to bio-oil properties [64] and quality [65]. Corrosion studies are now underway within the DOE program with initial results reported at conferences [65].

As outcomes from this research, a recent solicitation from OBP requested proposals for scale-up of bio-oil upgrading technologies to produce refinery compatible feedstocks. The participants funded include a team led by Iowa State University, Southern Research Institute, and a jointly led effort by Grace and PNNL. In addition, a new project at PNNL will investigate a range of hydrotreating of bio-oil in collaboration with VTT of Finland to produce storage stable fuel oil, renewable residential fuel oil, and liquid transportation fuels. The project will include techno-economic assessments and life cycle analysis. In the near future, the new scaled-up hydrotreater at PNNL will be used to produce the products for testing.

4.2.5. USDA research

In addition to their participation in the UOP-led Bio-oil Stabilization project and the NABC efforts in catalytic pyrolysis (described above), the ERRC of the ARS, under the leadership of Akasi Boateng, has published extensively on their process research on fast pyrolysis in recent years. They have processed such agriculturally-relevant biomass feedstocks as switchgrass and alfalfa stems [66], guayule shrub and bagasse [67], corn cobs and stover [68], barley straw, hulls and distillers dried grains and solubles (DDGS) from barley, [69] and oil-seed presscakes from pennycress and camelina [70]. In addition to these feedstock specific process results, the group has reported catalytic pyrolysis results using oak feedstock in both pyroprobe and bench-scale packed-bed systems [71] as well as pyroprobe GC/MS results with lignin and catalysts [72]. This technique was also applied to the guayule feedstock, without added catalyst [73]. Development of analytical techniques has also been a part of their research including NMR (proton and ¹³carbon) for characterization of bio-oil [73] and the water-insoluble fraction of bio-oil, along with GPC analysis [74].

4.2.6. University research

There are several universities in the U.S. that have become active in the biomass pyrolysis field over the past several years. The funding for this work comes from a number of sources, primarily DOE and USDA but also the National Science Foundation and private sources.

In addition to the participation in the NABC and leadership of a DOE bio-oil stabilization team, Iowa State University has an extensive program of research in biomass production and conversion. ISU in partnership with NREL and ConocoPhillips undertook a process study to compare pyrolysis with other biomass conversion technologies [75]. They conclude that pyrolysis is the low cost option based on their study. Other publications are also now appearing describing some of their fundamental studies of pyrolysis chemistry [76].

The group led by Profs. Wheeler, DeSisto and Frederick at the University of Maine has established a Forest Bioproducts Research Institute with a significant effort based on fast pyrolysis. A small bubbling fluidized-bed reactor has been developed and operated with pine feedstock giving fairly typical yields [77] and analytical capabilities for bio-oil analysis by proton and ^{13}C carbon NMR have been established [78].

At Washington State University, Prof. Manuel Garcia-Perez has initiated a program of research in thermochemical conversion of biomass that includes studies of fast pyrolysis in an auger reactor. He also has collaborated with other researchers, such as the Curtin University group of Prof. Li in Australia, where they are studying mallee wood pyrolysis in a fluidized-bed reactor [79–81]. Chemical modification of bio-oil was also studied [82] as well as recovery and fermentation of sugars in bio-oil [83] and bio-oil/biodiesel fuel blends [84]. Prof. Garcia-Perez has also collaborated with the Twente University group in fractionating bio-oil product vapors [85]. Other studies at Washington State have included feedstock pretreatment for pyrolysis [86] and micro-wave assisted pyrolysis [87,88]. The microwave assisted pyrolysis work by Prof. Hanwu Lei is a follow-up to his research at South Dakota State University [89] and the work initiated at the University of Minnesota by Prof. Ruan [90,91]. Due to its slower heating rate it is not true fast pyrolysis, but still results in significant bio-oil yields ranging up to 50%.

The group led by Prof. Philip Steele at Mississippi State University has become established in the field of biomass fast pyrolysis through their research in bio-oil production in an auger reactor [92]. They have reported results with pretreated pine wood [93] and wood plastic mixtures [94]. With a longer residence time of 30 s their reported bio-oil yields of 49–56% from hardwood and softwood are somewhat less than reported for true fast pyrolysis in fluidized bed reactors. They have also reported a study of the stability of bio-oil under exposure to UV radiation suggesting a degradation of phenolic components [95].

The Colorado School of Mines has recently reported a study of dynamic viscosity for several bio-oils and have confirmed earlier reports that bio-oil generally acts as a Newtonian fluid whose viscosity is highly dependent on the dissolved water content and also confirmed that separate aqueous and oil phases did not exist [96].

4.3. Demonstration activities

4.3.1. IBR-UOP

UOP LLC has taken a leading role in biomass fast pyrolysis and catalytic hydroprocessing to hydrocarbon fuels [97]. UOP is the lead for an Integrated Biorefinery project partially funded by \$25 M from DOE and \$12 M private funding to pilot biomass fast pyrolysis and catalytic hydrotreating for hydrocarbon fuel production of 60,000 gal/yr. The site preparations as well as the detailed design of the pyrolysis and bio-oil conditioning were complete as of April 2011. Pyrolysis fabrication and installation was completed early in 2012, while the upgrading final design was completed. Pyrolysis operations with bio-oil conditioning were underway in April 2012, while the upgrader will be fabricated and installed by 2013. The integrated system should be in operation in 2014.

4.3.2. IBR-GTI

GTI received funding from DOE to complete the design of process demonstration plant for their hydrolysis technology designated IH2. They received \$2.44 M along with which they will add \$0.63 M of private funding. The project R&D will extend from 2010 to mid-2012. A 50 kg/day pilot plant has been

constructed and planned start up was announced for the last quarter of 2011 [98]. The equipment has now been shaken down and is in full operation as of July 2012. GTI has licensed the technology to CRI Catalyst Company, which also provided much of the funding to build the pilot plant. The commercial plan specifies operation of a 5 t/d pre commercial scale demonstration (construction planned for 2013) followed by the beginning of commercial scale basic engineering by January 1, 2014 with construction underway by mid-year.

4.4. Commercial applications

UOP LLC has taken a leading role in biomass fast pyrolysis and catalytic hydroprocessing to hydrocarbon fuels through their partnership with Ensyn that has formed the joint venture company, Envergent. Due to favorable project economics from high liquid yield and technology flexibility, Envergent is directly commercializing biomass fast pyrolysis for energy production with four plants in design around the world.

KiOR is a commercial interest, who reports that they are developing catalytic pyrolysis and hydrotreating to produce hydrocarbon fuels. The details of the process have not been reported. A press release in late July 2012 related that the cellulosic gasoline fuel product had been permitted by U.S. Environmental Protection Agency (EPA) for use in the U.S. and sales to customers were to begin by the end of the year.

5. Canada

5.1. Ranking of fast pyrolysis in the area of bioenergy

Biomass is already one of the most utilized sources of renewable energy in Canada and accounts for approximately 650 PJ/a, mostly in the pulp and paper industry. The focus of most new bioenergy initiatives is on “value added” processes. Fast pyrolysis as a source of potential valuable chemicals and also of a densified/commoditized biofuel has been identified as a promising future technology.

A recent economic study led by Forest Products Association of Canada (FPAC) with the participation of Natural Resources Canada and FPInnovations has identified fast pyrolysis as having promising financial return [99]. The bio-pathways study indicates that some of the bio-product technologies such as pyrolysis have much better returns than conventional production. The most promising scenario involves sawmills and engineered wood products together with bio-refineries for production of pulp/bio-energy/bio-chemicals. Fast pyrolysis scenarios were projected to have a return on capital (ROCE) of +16 to 25% which was slightly better than most gasification-based cogeneration scenarios (10 to 15%) but much higher than scenarios for producing liquid fuels via gasification and chemical conversion of the product gas (less than 10%).

In 2010, the Canadian government announced the Investments in Forest Industry Transformation (IFIT) program to support Canada's forest sector in becoming more economically competitive and environmentally sustainable through targeted investments in innovative technologies [100]. The IFIT program provides Can\$100 million for projects that implement new technologies leading to non-traditional high-value forest products and renewable energies. IFIT's final Call for Proposals, which closed in September 2011, received a total of 107 applications representing Can\$2 billion in project proposals where the requested IFIT contributions amount to almost Can\$517 M, i.e., five times the available funding. The following shows the breakdown of all proposals to the IFIT program

and hence the relative priority which industry places on new technologies:

As can be seen from Fig. 4, approximately 50% of project proposals were bioenergy related and 9% of total projects were based on fast pyrolysis. In terms of bioenergy, torrefaction was the largest request based on a significant push by the electric power industry in Ontario to replace coal with renewable sources. Fast pyrolysis represents close to 20% of the bioenergy requests with the proposed plant size ranging from 6 to 400 t/day (input). All principal pyrolysis technologies were represented (screw, fluid bed, ablative) with proposed uses being mainly stationary fuel replacement (fuel oil) plus some co-generation and to a lesser extent bio-oil upgrading.

5.2. Research activities—Industrial

5.2.1. ABRI-Tech

A mobile auger-based fast pyrolysis system developed by ABRI-Tech [68] (Namur, Quebec) capable of pyrolyzing up to half a tonne per day (25 kg/h) of dried biomass feed was installed and tested at CanmetENERGY's laboratories in Ottawa. The pyrolysis process is based on a rotating auger which mixes heated ceramic or steel shot with biomass in order to produce pyrolysis vapours which are subsequently cooled and condensed. The system was tested under varying conditions to determine yield of bio-oil and char from hardwood sawdust. The yield of bio-oil from the system ranged between 44 and 62 wt% with water content determined by Karl-Fisher Titration in the 30–55% range resulting in calorific values in the 10–14 MJ/kg. Char and non-condensable gas samples were also collected and characterized. As a result of the testing program, recommendations were identified for further improvements. ABRI-Tech worked with CanmetENERGY, process engineers and its manufacturing partners to develop a '2nd generation' system. The company then moved the demonstration unit to its research facility in Namur, Quebec and in cooperation with industry partners continues to operate in Namur. As of March 2012, ABRI has sold a number of one ton/day pyrolysis demonstration units to Bioterre in Quebec, Alberta Innovates/Lakeland College in Alberta and USDOE Battelle Memorial laboratory in Ohio, USA. Recently, the Centre for Research & Innovation in the Bio-economy (CRIBE) announced a joint project with Domtar and Battelle Memorial for a biorefinery project in Ontario that will use the ABRI system as a core technology of the process [101].

ABRI-Tech has sold a number of units at the 1 dry tonne per day (DTPD) scale and is planning further developments to scale up to 50 DTPD in order to address industry requirements.

5.2.2. Agri-Therm

Agri-Therm is an offshoot of Western University's Institute for Chemicals and Fuels from Alternative Resources (ICFAR) which has developed a mobile fast pyrolysis unit for the production of bio-oil from biomass materials. The unit consists of an annular fluidized bed reactor where biomass is pyrolyzed. It surrounds a central cylindrical fluidized bed combustor where the non-condensable gases generated in the reactor are burned, thus making the process self-sustainable. The heat required by the endothermic pyrolysis reactions is transferred from the combustor to the reactor through special lift tubes. As noted below, in the section under Western University, Agri-Therm is working on developing 10 t/day unit and expects this design to be commercialized in 2012 [102].

5.2.3. Ensyn technologies

Ensyn is a producer of renewable liquid fuels and chemicals from non-food biomass feedstocks. Ensyn's technology is known as Rapid Thermal Processing™ (RTP™). RTP is a fast thermal conversion technology that has produced over 30 million gallons of renewable liquid and fuels over the last two decades. Ensyn's key renewable fuel product is Renewable Fuel Oil™, or RFO, a liquid fuel produced from wood and other non-food, cellulosic feedstocks. Ensyn has built several smaller scale commercial units for clients and also operates a fast pyrolysis plant, which was commissioned in 2007, next to a flooring production facility located approximately 90 km northwest of Ottawa, Ontario, Canada. Ensyn produces commercial quantities of bio-liquids at this facility and commercial testing is carried out on different feedstocks and reactor (RTP) configurations for clients interested in developing larger commercial facilities [103].

Ensyn has established a series of key strategic relationships with leading companies related to technology and engineering, feedstock supply and offtake applications. These relationships support Ensyn's key mission, which is to take advantage of its clear lead in the conversion of cellulosic feedstocks to liquid fuels and to build capacity and sales of RFO worldwide as soon as possible.

Ensyn's leading strategic relationships include:

- UOP, a Honeywell company—regarding engineering, RTP equipment supply and RFO upgrading to transportation fuels
- Chevron Technology Ventures—regarding RFO refinery applications and upgrading
- Fibria Celulose S.A.—a Brazil-based global leader in pulp production
- Felda Global Ventures—an affiliate of Felda Holdings Bhd, Malaysia's leading oil palm producer [104].

Ensyn has pursued energy conversion projects by combustion of bio-oil through collaborations with CanmetENERGY, BMA and Manitoba Hydro as described below.

In this area, Ensyn has led efforts at developing standards for bio-oil utilization through ASTM. "ASTM D7544—10 Standard Specification for Pyrolysis Liquid Biofuel" [105] ensures that pyrolysis oil, a liquid biofuel made from biomass such as wood chips or straw, maintains the highest levels of quality, reliability and performance when used as a fuel in industrial burners for the generation of renewable heat and power.

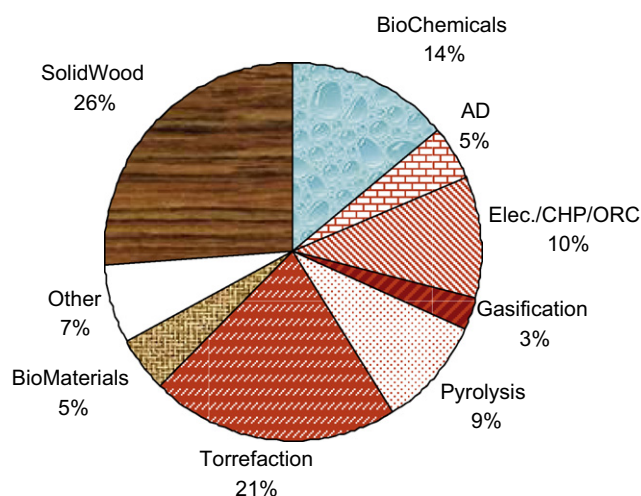


Fig. 4. Breakdown of all proposals to the IFIT program.

5.2.4. Resource Transforms International

An off-shoot at pioneering developments in fast pyrolysis at the University of Waterloo [106], RTI continues research on continuous, bench scale fast pyrolysis in a 2 kg/h fluidized bed pyrolysis unit in order to evaluate thermal behaviour of variety of biomass feeds and identify/quantify chemical components present in the water phase (Hodge' carbonyls, acids) [107]. The use of superheated steam is also investigated to increase yields of some components of pyrolytic liquid. The water-soluble fraction of pyrolysis condensates appears to be suitable for hydrogen production, synthesis gas production, hydrocarbons production via aqueous-phase catalytic conversion, and for some agricultural applications [108,109].

5.3. Research activities—Government

5.3.1. Natural resources Canada/CanmetENERGY

CanmetENERGY has long-standing collaborations in the area of fast pyrolysis with Ensyn and ABRI-Tech as noted above. In order to evaluate pyrolysis kinetics and bio-oil production from a variety of biomass fuels including agricultural residues, Canmet-ENERGY is currently constructing two 10 kg/h (feed) fast pyrolysis facilities. The designs under construction are based on bubbling fluidized bed and ablative principles and the two reactor designs will share identical ancillary equipment. Commissioning is scheduled to start in autumn of 2012.

CanmetENERGY has carried out research on catalytic hydro-processing of biomass-derived pyrolysis oils (bio-oils) to liquid biofuels. Using experimental data obtained with a semi-batch 300 ml autoclave, an approach was developed to upgrade bio-oils to stable products compatible with current distillate streams in oil refineries and potentially compatible with conventional transportation fuels. CanmetENERGY has identified promising formulations for a relatively inexpensive well-dispersed catalyst coupled with use of a liquid medium ("solvent") in which the bio-oil can react. Oxygen removal rates exceeding 90% were consistently obtained. CanmetENERGY has constructed a continuous reactor system and commissioning is presently underway.

CanmetENERGY has extensive bio-oil combustion facilities and has successfully fired a number of bio-oil grades at rates up to 200 kg/h [110–113]. A current project in partnership with Ensyn Technologies and Brais, Malouin and Associates (BMA) is investigating the combustion of pyrolysis oil in a stand-alone, certified small scale industrial burner. A range of test conditions were evaluated to determine flame stability, quality and emissions at varying pyrolysis flow rates (up to 200 kg/h). The data from these runs is already being used to implement some modifications to the test equipment and to validate a computational fluid dynamics model developed by BMA.

The identification and valuation of chemicals within fast pyrolysis oils is an active area of research for a number of universities in Canada as well as CanmetENERGY, Agriculture and Agri-Food Canada, FPInnovations, Canadian Forest Service and Canada's National Research Council [114,115]. Efforts, with some coordination, are underway to identify the most abundant chemicals, determine the effect of feedstock properties on chemical distribution and quantify the potential revenue that could be derived from different applications of pyrolysis oils [99,116].

5.4. Research activities—Academic

5.4.1. École Polytechnique de Montréal

The Centre De Recherche En Ingénierie De Procédés—Bioraffinage (CRIP) is developing state-of-the-art biorefinery processes and evaluating the feasibility of integrating these systems into existing factories and industrial installations. The primary focus is

on developing the potential for production of energy and hydrocarbons from urban biomass waste. In the area of pyrolysis CRIP Director, Professor Jamal Chaouki is investigating microwave-based pyrolysis. Research is being carried out by modelling and experiments using a commercially-available 3200 W research-grade microwave oven. The focus of the work is based on water molecules having a higher affinity to microwave energy leading to water vaporizing first resulting in enhanced porosity prior to volatilization of the organic material. It is expected that this would lead to lower non-condensable gas production and higher energy/lower oxygen pyrolytic vapours [117].

5.4.2. University of Toronto

Since 2006, the Combustion Research Laboratory at the University of Toronto has been actively involved in fast pyrolysis liquid research. The goal of the research program, directed by Professor Murray J. Thomson in the department of Mechanical and Industrial Engineering, is to demonstrate bio-oil's potential as a renewable 2nd generation biofuel by producing heat and electricity in a Stirling engine. First, to understand the combustion properties of pyrolysis liquid relative to conventional hydrocarbon fuels, a 10 kW spray based swirl burner with air-blast atomization, pilot flame ignition and air preheat was constructed. The burner was tested with a hardwood derived bio-oil/ethanol blend (80/20 by % volume) under a wide range of operating conditions and compared to No. 2 (diesel) and No. 4 (heavy) fuel oil using gaseous and particulate matter (PM) emissions diagnostics, as well as flame imaging techniques. Results indicate that stable combustion and thorough burnout (up to 99.5% fuel carbon conversion efficiency) are achievable with pyrolysis liquid by adjusting available burner parameters, such as the degree of swirl or air preheat. With a larger burner (> 200 kW), and thus longer hot residence times, the unburned hydrocarbon (UHC), CO and solid carbonaceous residue (CR) emissions could be reduced to very low levels [118–120].

Concurrent with the above research, Professor Thomson's team has been working with a Whispergen™ combined heat and power (CHP) Stirling engine (5.5 kWth, 0.8 kWe). The system was originally designed as a CHP unit for boats and works with an evaporative diesel burner. The engine has been modified to run successfully with bio-diesel, ethanol and most recently, 80/20 volume % bio-oil/ethanol blends. A spray burner was adapted to the unit and run using a zero-ash, low solids (0.03 wt%) bio-oil in order to produce 7.5 kWth and 0.3 kWe [121].

5.4.3. University of Western Ontario

Western University opened the Institute for Chemicals and Fuels from Alternative Resources (ICFAR) in October 2009. The Institute, originally founded by Franco Berruti and Cedric Briens, has recently become the home of the NSERC-FPInnovations Industrial Research Chair in Forestry Biorefinery (Charles Xu) [122]. Over the past two years, it has grown to become a very large research and development centre, focussing on biomass thermochemical conversion technologies (torrefaction, pyrolysis, gasification, hydrothermal conversion and upgrading processes) [123–125]. Today, the research team consists of three full time faculty members, 30 graduate students at the Master and PhD levels, 7 postdoctoral fellows, 3 technical support staff and 3 administrative staff members. The Institute carries out R&D activities in collaboration with industrial institutions worldwide and it receives also considerable government grants. Technology transfer and commercialization are also goals of the Institute.

Agri-Therm is one of the successful spin-offs of the activities of ICFAR [102]. Agri-Therm's mobile modular design is based on fluidized bed technology and operates on a heavy duty, standard

size pull trailer for easy transportation and set-up. The unit is also collapsible, making it safe and energy efficient to transport over existing roads and off-road right-of-ways. Agri-Therm has been developing a 10 t/day mobile pyrolysis technology for the production of bio-oil and bio-char from a variety of agricultural and forestry residues. Currently, the second-generation (pre-commercial) of the mobile converter is being built and it will be commissioned in 2012. It is anticipated that the technology will become commercially available by the end of 2012.

5.5. Commercial and demonstration activities

5.5.1. Domtar

Montreal-based pulp and paper company Domtar is partnering with Battelle, an independent research and development specialist in Columbus, Ohio, to test a new technology that rapidly converts wood waste into crude bio-oil and gas. This new public-private partnership (The publicly-funded Centre for Research and Innovation in the Bio-Economy (CRIBE) is providing up to \$6 million in funding to leverage a total project value of up to \$14 million) is set to drive revenue for the forest products industry in Northern Ontario. In this two phase project, Phase 1 will utilize wood waste from Domtar's Dryden pulp mill to produce the higher value bio-oil at the pilot plant scale. Once the process is optimized and results are demonstrated, phase two involves the construction of a 100 t/day pilot plant, to be integrated into the Domtar pulp mill.

The technology being employed in this project is based on the ABRI-Tech design with modifications by Battelle. The key to Battelle's approach is in the treatment and processing of this crude bio-oil to a "drop-in fuel", which can be blended directly with gasoline or diesel fuel. Domtar Dryden will use wood waste, which is currently burned for low value, as the biomass feedstock for the process. If successful, the bio-oil will be used to blend into the fuel for Domtar's vehicle fleet or it could be used internally to offset the use of natural gas [101].

5.5.2. Dynamotive

In April 2005 Dynamotive completed its first demonstration scale plant at West Lorne, Ontario designed to produce up to 100tpd based on its bubbling fluidized bed technology. The ~\$20 M West Lorne BioOil Cogeneration Project would deliver up to 2.5 MWe to the grid from its Orenda turbine (developed by Magellan Aerospace) and was partially funded with a Cdn \$5 million contribution from Sustainable Development Technology Canada (SDTC), a foundation created by the Government of Canada to support the development and demonstration of clean technologies [126]. In 2010 the West Lorne plant was put into receivership and the plant components auctioned to the highest bidder.

In 2006 Dynamotive broke ground for the MegaCity Recycling, 200 t per day bio-oil plant site in Guelph, Ontario. The plant is not currently operating. Dynamotive has continued to announce various initiatives; however the authors have been unable to confirm any definitive projects.

5.5.3. Ensyn technologies

Ensyn operates a fast pyrolysis plant, which was commissioned in 2007, next to a flooring production facility located approximately 90 km north-west of Ottawa, Ontario. Ensyn produces commercial quantities of bio-liquids at this facility and testing is carried out on different feedstocks and reactor (RTP) configurations. The principal RTP unit at Renfrew has a nominal processing capacity of 75 dry tonnes per day (150 t per day of green material). However, it routinely operates at capacities in excess of its nominal design rate, with a maximum demonstrated

processing capacity of 100 dry tonnes per day. The actual capacity depends on the nature of the biomass feedstock being converted. The facility incorporates the principal RTP unit as well as smaller testing RTP facilities, liquid fuel handling facilities and chemical processing units.

In what would be the world's largest fast pyrolysis plant, Ensyn has proposed a 400 dry tonnes per day in Alberta to convert sawmill residuals from Tolko's High Level sawmill into 75 million liters per year of pyrolysis oil using Ensyn's proprietary RTP technology. The sawmill residuals at the mill are currently incinerated in a conical waste (beehive) burner for no value. A small portion of the pyrolysis oil will be used as an ingredient in the resin used to manufacture of the wood panel products such as OSB and plywood at production facilities of Tolko and potentially other manufacturers. The majority of the pyrolysis oil will be sold to customers who will utilize it to displace fuel oil [103].

5.5.4. Manitoba Hydro

Manitoba Hydro is the major energy utility serving the Province of Manitoba. Manitoba Hydro in conjunction with the utility's host site customers will be showcasing five pathways for converting raw biomass into useful energy. The five pathways include pyrolysis oil, syngas, waste heat, biogas and biocarbon. The installed capital cost of commercial Renewable & Clean Energy (RCE) Systems based on the chosen pathways are anticipated to average \$3500 to \$5000 per kW electrical. Each of the technologies associated with each pathway are modular and thereby afford the opportunity to be mass produced and installed with minimal cost.

The Pyrolysis Oil Demonstration Project involved the production and use of pyrolysis oil as a replacement for heavy fuel oil in a large scale combined heat and power (CHP) system at the Tolko Kraft Paper Mill in The Pas, Manitoba [127]. The mill relies on a combination of hog fuel, waste oil, and bunker C (no. 6 fuel oil) to fuel a power boiler for the production of high pressure steam for process heat and electricity. The equipment and services for this project were provided by Ensyn Technologies Ltd., based in Ottawa, Ontario. The co-firing demonstration successfully fired over 60,000 l of bio-oil in 2010 with stable combustion and extensive emissions monitoring showing improved boiler performance. A second demonstration is planned for a grain drying operation where bio-oil will replace propane.

5.5.5. Pyrovac

Pyrovac in 1998 completed its vacuum-assisted pyrolysis plant (84 t/d feed, mainly bark) in Jonquière, Quebec and operated for approximately 2000 h before being mothballed. Recently it has been announced that the plant has been sold to the USA-based company Three Dimensional Timberlands (TDT). The plant will be moved to the city of Gold Beach, Oregon where it's initial focus will be to produce biochar. Dr. Christian Roy, developer of the Pyrovac technology will act as a consultant to TDT on the new plant commissioning and operation [128].

6. Germany

6.1. Ranking of fast pyrolysis in the area of bioenergy

Biomass is one of the most important and most diverse renewable energy sources in Germany. Biomass is used in solid, liquid and gas form to produce electricity and heat and to manufacture biofuels. Around 69% of total final energy from renewable sources was covered by the different types of biomass used to this end in 2007. In Germany, bioenergy (based on final energy consumption) accounted for 3.9% of total electricity

consumption, 6.2% of total heat demand and 7.6% of total fuel consumption.

The use of bioenergy is to be further expanded. The technical potential required for this is available in Germany. In the agricultural and forestry sector, part of the 17 million hectares of agricultural land (approx. 12 million hectares of arable land and approximately 5 million hectares of grassland) and of the 11 million hectares of woodland are available for biomass production.

Fast pyrolysis plays a minor role in Germany and is only deployed in two larger projects:

- Bioliq-process developed by KIT (Karlsruhe Institute of Technology) together with the firm LURGI using their twin screw mixing reactor (sand cracker). The produced bio-oil and part of the char are mixed to form a stable slurry which will be transformed syngas in an entrained pressurized flow gasifier with subsequent direct synthesis of dimethylether (DME).
- BTO-process (Biomass-to-Oil) developed by PYTEC Ltd., Hamburg, using an ablative reactor with a design capacity of 6tpd. PYTEC's activities are also directed to the combustion of bio-oil in a diesel engine of a CHP plant. The process has been under development since 2003. The pilot plant was moved in autumn 2012 from Bülkau to Hamburg and is currently refurbished with the help of a global strategic partner.

6.2. Research activities

6.2.1. DBFZ

The scientific task of the Deutsches BiomasseForschungsZentrum (DBFZ) is to comprehensively support the efficient establishment of biomass as a valuable resource for sustainable energy supply within the scope of applied research and to drive it forward, both theoretically and practically. The establishment and integration of biomass in the range of existing energy sources takes place with simultaneous inclusion of technical, ecological, economic, social and energy management aspects along the whole usage chain, i.e., from production through to supply and use. In addition, the DBFZ is to draw up sound decision-making aids for politicians.

The “Thermo-Chemical Conversion” (TK) department deals with selected issues related to the thermo-chemical conversion of biogenic solid fuels and the supply of electricity and/or heat from biogenic solid fuels. All technical aspects of the fuel, from the furnace through to integration in the local energy system and the flue gas cleaning, are taken into account, both theoretically in the monitoring and practically in the development. Furthermore, the theoretical principles, including modeling of the fundamental thermo-chemical processes, are also considered.

Use of solid biomass as an energy source must continue to increase significantly in order to further extend the proportion of renewable energy production in Germany—as required politically within the scope of the climate protection initiative. At the same time, this increase must take place within the thermo-chemical conversion with the least possible impact on the environment—especially with respect to fine dust, organic pollutants and nitrogen oxides (NO_x).

Against this background, among other things, the TK department examines how, apart from wood, other biogenic solid fuels (e.g., from agriculture) can also be made available for energetic use. In addition, state of the art standards must be improved, existing combustion systems further optimized and new equipment developed. The main objectives are to increase efficiency, lower effects on the environment and reduce costs. Other objectives within this context are improved integration of solar

systems via innovative control systems and the development and optimization of cogeneration (CHP) systems in all output ranges.

6.2.2. TU Bergakademie Freiberg

The TU Freiberg has been active in investigating the pyrolytic behavior of different biomasses and lignites in order to determine heat requirements and to establish mass balances. Apart from TG_DSC analyses, a small scale pyrolysis unit has been used for collecting data on the mass distribution of liquid, solid and gaseous products. A screw reactor is available (10 kg/h) for slow pyrolysis which was used to study the recyclability, character and behavior of different biomass ashes.

6.2.3. University of Rostock

The University of Rostock, department for Energy Systems have been active in testing combustion and emissions from pyrolysis oils using a burner attached to a flame tunnel as well as micro-turbines. Recently they have performed corrosion tests with bio-oils [129–131].

6.2.4. Fraunhofer UMSICHT, Oberhausen

Fraunhofer UMSICHT, Oberhausen has been developing applied and custom-made process engineering technologies. Within their biorefinery activities “Fraunhofer UMSICHT” is currently establishing a technical center for biomass including also a pilot plant for ablative fast pyrolysis with a new reactor design.

6.2.5. Thünen Institute of Wood Research

The Thünen Institute of Wood Research has been active in fast pyrolysis since 1982. Several devices are available:

- (1) For analytical pyrolysis a CDS pyroprobe directly attached to a GC/MS system had been used for many years to obtain data on pyrolysis products from biomasses and cell wall constituents. The experiments were used to build up a mass spectral library of thermal degradation products used for bio-oil analysis [132–135].
- (2) A couple of years ago the pyroprobe system was replaced by a Frontier-system which comprises an autosampler and a micro-furnace for pyrolysis. The pyrolyzer is attached to a GC equipped with FID and MS. The FID signal is used for quantification and the MS-signal is used for identification.
- (3) A modular mini-pyrolyzer is used to pyrolyze batch samples in the 10–50 mg scale. The system consists basically of quartz tubes which can be connected which each other. After the reactor tube, a tube for catalysts or for cooling can be coupled. The sample is heated within some seconds by sliding the preheated metal tube over the sample. Bio-oils can be dissolved with solvents mixed with internal standard to obtain quantitative results. Gases are collected in a bag The whole system can be weighed before and after to establish mass balances [136].
- (4) A 300 g/h bubbling fluid bed reactor equipped with continuous feeder, cooler and electrostatic filter is operated to obtain preparative samples of bio-oils. The system helps to get data which are closer to larger pyrolysis systems. Thus oil and char yields as well as oil characteristics and composition can be determined [137].
- (5) A bubbling fluid-bed system with a design capacity of 5 kg/h and circulation of the fluidization gas has been operated since 1995. The hot vapors can either be directed to a condensation train or a quench system. The condensation train consisting of 3 condensers and one electrostatic precipitator. Thus bio-oil can be fractionated on-line into sugar enriched and lignin

enriched samples. The quench system is operated with an iso-paraffinic liquid as cooling medium [138].

6.2.6. Leibniz Institute for Catalysis (LIKAT)

The Leibniz Institute for Catalysis at the University of Rostock (LIKAT) is the largest publicly funded research institute in the field of applied catalysis in Europe. The main areas of interest of the LIKAT are homogeneous and heterogeneous catalysis. Recently, LIKAT is active in the project: Upgrading of fast pyrolysis liquids with the CLC process (Catalytic Liquid Conversion). The work is focused on the heterogeneously catalyzed deoxygenation of pyrolysis oil in hot compressed water to produce fuel components [139].

6.3. Demonstration activities

6.3.1. KIT (Bioliq)

The bioliq[®] process, developed at the Karlsruhe Institute of Technology (KIT), aims to produce synthetic fuels and chemicals from biomass. Syntheses based on synthesis gas require pressures of up to 10 MPa. Therefore, gasification already at elevated pressures may omit expensive gas compression and ease gas cleaning and conditioning. High-pressure entrained-flow gasification provides high quality, tar-free syngas with low methane contents. For that purpose a feed is required, which can easily be fed to the gasifier at elevated pressures being atomized by oxygen as the gasification agent. Fast pyrolysis was chosen as a most promising process to obtain such a feed by mixing pyrolysis condensates and char to a so called bioliqSyncrude[®], exhibiting a sufficiently high heating value, and being suitable for transport, storage and processing. This slurry-gasification concept has been extended to a complete process chain via a pilot plant erected on site at KIT.

The three subsequently constructed parts of the plant, funded by the German Ministry of Food, Agriculture, and Consumer Protection, consist of the fast pyrolysis and biosyncrude production, the 5 MWth high-pressure entrained-flow gasifier operated at up to 8 MPa (both in cooperation with Lurgi GmbH, Frankfurt), as well as the hot gas cleaning (MUT Advanced Heating GmbH, Jena), dimethylether and final gasoline synthesis (Chemieanlagenbau Chemnitz GmbH). The last components aim at the improvement of syngas utilization by saving energy, simplifying process technology and improving product quality. The general project was launched in 2005, when design of the

pyrolysis plant commenced, followed by mechanical completion in 2007 and commission in 2008. Gasification, gas cleaning and syntheses production plants will be completed by the end of 2011. In order to use a broad variety of residual biomass typically having low volumetric energy content (e.g., straw, hay, or residual wood from agriculture, forestry and land cultivation), fast pyrolysis plays a key role in the process. The technical concept of the pilot plant in Karlsruhe is based on the Lurgi-Ruhrgas mixer reactor, previously devoted to coal degassing or heavy crude coking. The intentional design of biomass conversion was based on a series of tests with several types of straw and wood conducted in relevant bench scale plants of KIT and Lurgi Lentjes, Frankfurt. The actual flow scheme is depicted in Fig. 5.

So far, four test campaigns, with typically one week full shift operation included, have been conducted—mainly testing the functionality and to establish operation procedure and protocols. Operation targets for the future are:

- to achieve full operation of the plant with straw as feed material;
- to create a closed mass and energy balance;
- to produce relevant amounts of representative pyrolysis products and biosyncrudes.

6.3.2. PYTEC

PYTEC, in cooperation with its sister company TEC, has been developing the BtO-process, an innovative pyrolysis process for the thermal conversion of wood to bio-oil. Since December 2005 the first pilot scale plant has been operating designed for 4 t of bio-oil per day fast ablative pyrolysis. Aimed at the economical generation of heat and power from biomass, the produced bio-oil has been tested in a CHP-plant with a Mercedes-Benz engine [140,141].

6.4. Commercial applications

None so far.

7. Finland

7.1. Ranking of fast pyrolysis in the area of bioenergy

The production of fast pyrolysis bio-oils from biomass is one alternative to replace fossil fuels where liquid fuels are needed.

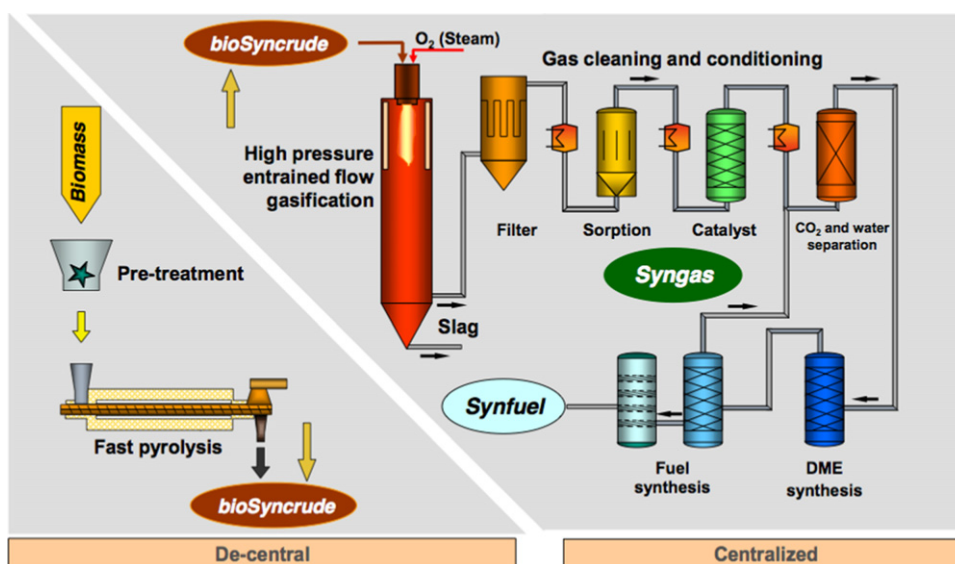


Fig. 5. Schematic of the bioliq-process.

The main advantage of fast pyrolysis is in biomass and bio-oil logistics. Extra biomass (compared to existing heat loads) is often available at sites, where combined-heat-and-power is produced (for example district heating plants, forest industry sites). Bio-oil is a dense energy carrier and it will be initially used as fuel oil. The alternative for using the extra biofuel for the CHP plant is to generate more power with a partly condensing turbine. However, condensing head has only a total efficiency of about 25–30%, whereas bio-oil may be exported from the site to high value users. Integrated pyrolysis offers additional benefits when compared to stand-alone pyrolysis. It is flexible and easy to operate, has a high overall efficiency compared to stand-alone concepts, has lower investment costs due to no need for a specific char combustor (effects to the cost of the main boiler are considered marginal), has lower operating costs than stand-alone pyrolysis, and use of by-product in the main boiler. In Finland there is increased interest in fast pyrolysis, both in stand-alone (Green Fuel Nordic) and integrated (Fortum) concepts.

7.2. Research activities

7.2.1. VTT (Technical Research Centre of Finland)

VTT is carrying out research on pyrolysis with two types of projects. The industrial project supports the consortium of Metso Power, UPM Kymmene and Fortum in their effort to demonstrate pyrolysis oil production and long-term use [142–146]. The national Tekes (the Finnish Funding Agency for Technology and Innovation) project aims to create the basic tools for commercialization of pyrolysis oil production and use, including to create standards and norms for pyrolysis oils. This involves the work on MSDS [147,148], participation on ASTM standardization [65] with Ensyn and PNNL, initialization of standardization in Europe under CEN, developing and validating test methods for pyrolysis oil specifications, and on-line methods for process quality control. In addition, chemical characterization [149,150] and methods for measuring stability [8,64,151–154] for whole pyrolysis oil is further developed. The work involves also work on modeling of biomass pyrolysis. Experiments are conducted in entrained and bubbling fluid bed pyrolyzers (20 kg/h), 1 kg/h fluid bed unit, and continuous-flow hydrotreatment unit (20–30 g/h).

7.2.2. Consortium (Metso, Fortum, UPM, and VTT)

Metso, Fortum, UPM, and VTT have developed the world's first integrated bio-oil production concept, where heat for pyrolysis is transferred from hot sand of a fluidized-bed boiler [144]. The consortium has constructed a 7tpd bio-oil production pilot unit in which the pyrolysis reactor is integrated with a pilot fluidized-bed boiler. The integrated pyrolysis concept enables both high overall efficiency and high bio-oil yield. By-products such as char and non-condensable gases are utilized in an adjacent boiler to

produce heat and electricity. The integrated concept is easy and smooth to operate, and has good control characteristics. Proof-of-concept has been carried out: since 2009 more than 100 t of bio-oil have been produced from sawdust and forest residues at high availability. Around 40 t of bio-oil have been successfully combusted in Fortum's 1.5 MW district heating plant in Masala, Finland, with high efficiency. Flue gas emissions were close to those of heavy fuel oil.

Development of the concept has been supported by experimental work on fast pyrolysis at VTT. Various industrially relevant feedstocks have been tested using VTT's fluidized-bed units [142]. Analytical methods [147,149,150] for both whole oil characterization and determination of fuel oil quality have been developed. Product quality has been controlled throughout the utilization chain from biomass processing and bio-oil production to final combustion in an industrial boiler. New on-line analyzer [145,147] for observing changes in water has been developed. Good quality homogenous bio-oil has been produced with high organic yields (55 to 60 wt% of dry pine feedstock).

7.2.3. Åbo Akademi University

At ÅA pyrolysis, and gasification of black liquor (bio-product derived from pulping industry) is being studied in laboratory-scale units. The purpose is to better understand the fate of the pulp cooking chemicals, sulphur and sodium, in novel thermal conversion processes being planned. Black liquors contain typically 20% (fuel dry solids) of sodium and 3–6% sulphur. These elements need to be recovered and reused in the pulping process, but their behavior in pyrolysis and gasification is partly unclear and requires laboratory studies at controlled conditions using thermal gravimetric analysis, grid heaters and other small scale reactors.

Also production of pyrolysis oil from solid woody biomasses is studied using a special type of dual reactor laboratory system. In the first reactor the biomass is pyrolyzed in a fluidized bed, and the vapors are fed to the next reactor. The second reactor is also a fluidized bed reactor but the bed material consists of zeolite based catalyst particles. The system has made it possible to study in-situ catalytic upgrading of the pyrolysis vapors under very well defined conditions [155].

7.3. Demonstration activities

7.3.1. Consortium (Metso, Fortum, UPM, and VTT)

VTT together with its partners have identified considerable potential for the deployment of fast pyrolysis in industries with established infrastructures, such as the pulp and paper and mechanical wood processing industries in Europe [156] and North America [157]. Integration of fast pyrolysis and forest industry boilers is technically viable, and the opportunity is considered

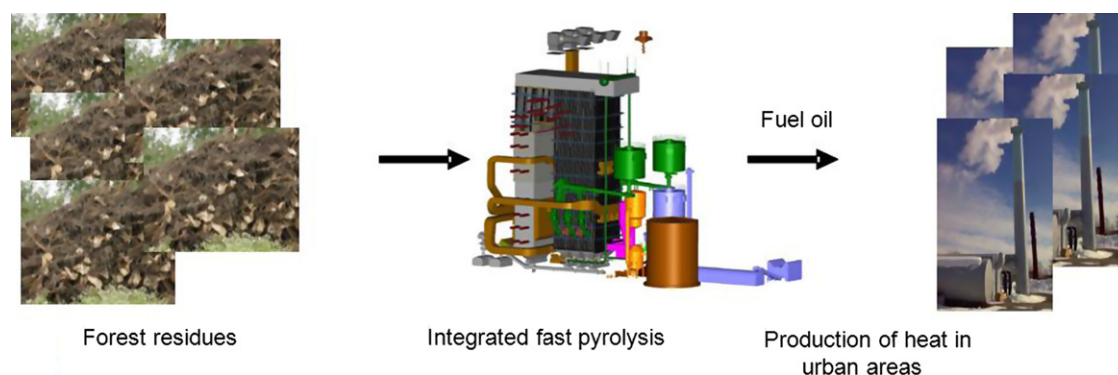


Fig. 6. Phased implementation of biofuel industry based on integrated pyrolysis—demonstration plant.

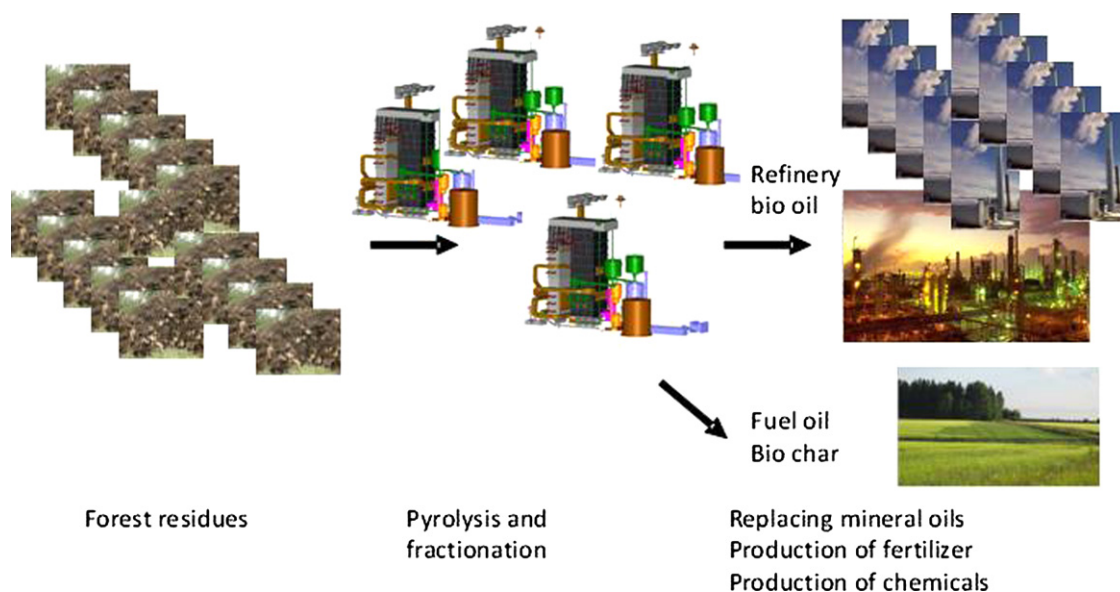


Fig. 7. Phased implementation of biofuel, fertilizer and chemical co-production—building capacity.

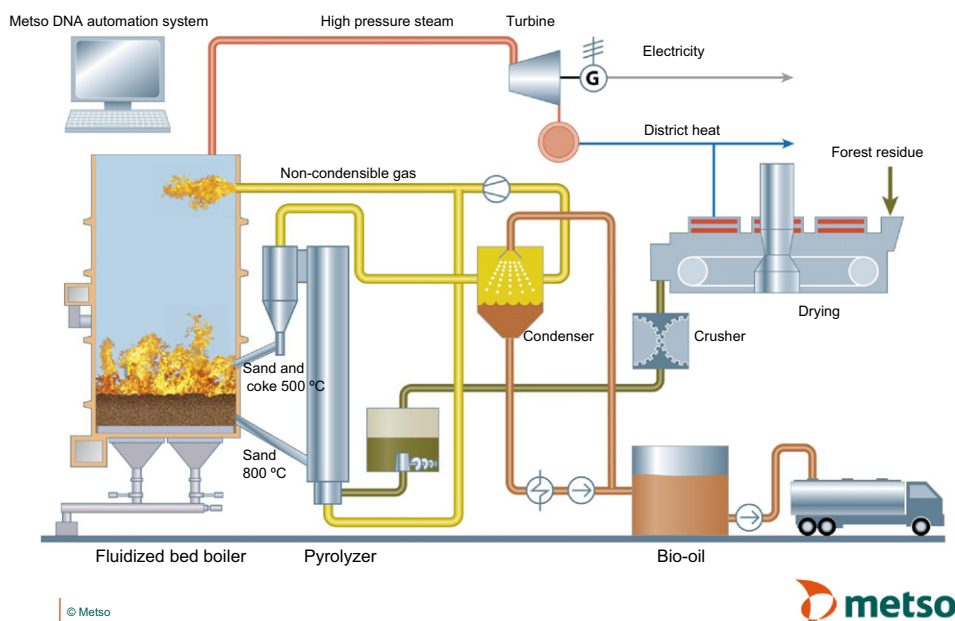


Fig. 8. Industrial-scale integrated bio-oil plant in Joensuu, Finland.

industrially relevant. The first uses for the bio-oil would probably be in replacing fuel oils in industrial ovens and boilers. However, a longer term goal would be to produce co-feedstock for mineral oil refineries for the production of transportation fuels and petrochemical feedstocks. This approach has been developed, for example, within the EU's recently completed BIOCOUP project [158].

Phased construction of biofuel capacity may be a technically low-risk approach to building new 2nd generation transportation biofuel capacity meaning that technically less demanding uses for bio-oil may be developed initially. Industrial demonstration project (Fig. 6) of integrated fast pyrolysis has already been announced by Fortum (see below for more information). After demonstration is complete, more production units may be built, which may in the future be used to co-feed a mineral oil refinery (Fig. 7).

Fortum has announced that it will invest in the commercialization of integrated fast pyrolysis technology by building a bio-oil

plant connected to the Joensuu combined heat and power production plant (CHP) in Finland. The integrated bio-oil plant will be unique on an industrial scale. The integrated CHP plant in Joensuu will produce heat, electricity and 50,000 t of bio-oil per year. The bio-oil raw materials will include forest residues and other wood based biomass. The new technology has been developed into a commercial scale concept in cooperation between Fortum, Metso, UPM and VTT as part of TEKES Biorefinery research program. Construction of the bio-oil plant will commence during 2012, and the plant is expected to be in production in the autumn of 2013. Bio-oil production will increase the energy wood consumption at Joensuu power plant almost doubling the use from the existing 300,000 m³ per year (Fig. 8). [<http://www.fortum.com/en/mediaroom/pages/fortum-invests-eur-20-million-to-build-the-worlds-first-industrial-scale-integrated-bio-oil-plant.aspx>].

7.3.2. Green Fuel Nordic

Green Fuel Nordic Oy (GFN) is a Finnish biorefinery company which was established in 2011. It has a headquarters in Kuopio, in Eastern Finland. GFN's business idea is to refine second generation liquid fuel derived from forest-based raw materials by using commercially proven technology. The company plans initially to build three 400 BDMTPD (Bone Dry Metric Ton Per Day) biorefineries, with a combined annual production capacity of 270,000 t of bio-oil. The amount of forest-based raw material needed for three facilities is one million solid cubic meters per year.

Green Fuel Nordic Oy has announced an investment roadmap for production of second generation bio-oil from sustainable, forest-based feedstocks using fast pyrolysis technology. GFN has signed a memorandum of understanding with Envergent Technologies LCC, a Honeywell company, under which the two companies would collaborate on projects to convert biomass to renewable fuel.

The conversion of pre-treated biomass into liquid biofuel is done by using Envergent's RTP™ (Rapid Thermal Processing) technology. The sizing and drying of feedstock material into desired particle size and moisture content required by Fast pyrolysis system is done in Biomass handling system. Ultimately the produced bio-oil is handled and stored in Bio-oil storage system.

The main applications for liquid biofuel are industrial boilers, district heating and lime kilns that can utilize bio-oil with only minor modifications to the existing systems [159]. Other feasible applications are marine applications, particularly slow- and medium-speed diesel engines. Future applications can be found in upgrading bio-oil into transportation fuel and extraction of chemicals for the use in chemical industry, pharmaceuticals, cosmetics, and many more.

Green Fuel Nordic Oy is planning to build multiple biorefineries in Eastern Finland and they are currently looking for other potential locations. According to Timo Saarelainen, the CEO of Green Fuel Nordic, the future target is to build up to 20 biorefineries in Finland. The first biorefinery is planned to start commercial operation in the last quarter of 2014.

8. The Netherlands

8.1. Ranking fast pyrolysis in the area of bioenergy

In 2010, a total renewable energy production of 86.2 PJ has been realized in the Netherlands, which is only 3.8% of total gross energy end use in the Netherlands (total energy use: 2245 PJ). The goal of the Netherlands is 14% renewable energy in 2020. Energy from biomass is one of the main renewable energy sources in the Netherlands and accounts for almost 75% (64.1 PJ) of total renewable energy production. Biomass is followed by wind energy which accounts for almost 20% of production [160].

Within the biomass category, the main contributors are waste incineration, co-firing of biomass in power plants and wood fired stoves used by households. These options all contribute around 20% to the amount of bio-energy generated. Within the Netherlands around 50% of the renewable energy is used to generate electricity, around 40% to generate heat and 10% is used for transport.

Currently, renewable energy generation from pyrolysis oil does not play a role in the Netherlands, but it is expected that this will change in the coming years. In the new Dutch incentive program on the promotion of renewable energy (SDE+) a special category has been introduced for heat and/or power from liquid biomass. To qualify for this SDE+ subsidy the liquid fuels need to

fulfill certain sustainability criteria, which are not considered to be a problem for pyrolysis oil produced from biomass and residues.

The first commercial-size, fast pyrolysis plant is currently being developed in Hengelo, the Netherlands. This plant – also called the EMPYRO project – will have a capacity of 25 MWth biomass input and producing around 22 kton of pyrolysis oil a year. Additional production capacity might be realized in the Netherlands or pyrolysis oil might be imported.

8.2. Research activities

8.2.1. BTG Biomass Technology Group BV

BTG has a number of test facilities for developing the fast pyrolysis process itself as well as for pyrolysis oil applications [161].

8.2.1.1. Fast pyrolysis process. For further development, process optimization, feedstock screening and production of pyrolysis oil BTG has 2 units available. A small, 1–5 kg/h pyrolysis unit is used for screening biomass and establishing initial mass and energy balances. The pilot plant (up to 200 kg/h of biomass) is used to generate more detailed engineering data and to produce larger quantities of pyrolysis oil (up to a few tons). For the market introduction and further commercialization of the BTG fast pyrolysis technology daughtercompany BTG-Bioliquids BV has been established.

8.2.1.2. Pyrolysis oil applications. Diesel engine: Using pyrolysis oil in a diesel engine is considered for CHP-application in the capacity range below 1 MWe. A one cylinder, diesel engine has been modified to enable the fuelling of this acidic fuel. Main modification concerns the construction and installation of a completely stainless steel fuel injection system. First results are very promising and work will be continued. A test of 40 h was carried out with 100% pyrolysis oil without any notable effect on fuel consumption and flue gas emission [162].

Pyrolysis oil gasification: The gasification of pyrolysis oil at elevated pressure and with oxygen might be an interesting approach to produce syngas. Two different approaches are followed at BTG. A small unit is available to mimic the performance of an Autothermal Catalytic Reformer using commercial and dedicated catalysts. The second approach is performed in cooperation with etc (Piteå, Sweden) [163]. Test campaigns are being planned in the 3rd quarter of 2012 to gasify pyrolysis oil in their pressurized, oxygen blown entrained flow gasifier.

Pyrolysis oil upgrading: The aim is to stabilize the oil, and to enable further treatment/upgrading to a transportation fuel. In this so-called 'HDO process', pyrolysis oil is treated with hydrogen at elevated pressure in the presence of a catalyst [164,165]. The resulting oil can be co-refined in existing refineries or further upgraded to different biofuels. In BTG's laboratory two units are in operation to develop this process further. The smallest one has an oil input capacity of a few hundred ml per hour; the second unit can treat up to 4 l/h depending on the required reaction severity. In the process a proprietary catalyst is applied, which has been developed and patented jointly with Rijksuniversiteit Groningen (RUG) and the Boreskov Institute of Catalysis, Novosibirsk, Russia.

Pyrolysis oil fractionation: In 2011 a pilot plant has been built to separate the lignin fraction from pyrolysis oil. The fractionation unit is typically operated at a capacity of 12 kg of pyrolysis oil/h producing 3 kg of 'pyrolytic lignin'. BTG developed a modified recipe to produce a phenol/formaldehyde resin from this lignin with up to 50–75% replacement of the fossil phenol. Furthermore, the use of the pyrolytic lignin as bitumen replacement in asphalt and in roofing material is planned for demonstration 2012.

8.2.2. ECN—Energy Research Centre of the Netherlands

8.2.2.1. Lignin pyrolysis. Within the framework of the EU FP7 IP- BIOCORE project, ECN is investigating the thermochemical conversion of lignin for the production of phenols. The preferred technology is (fast) bubbling fluidized bed (catalytic) pyrolysis. The activities mainly deal with the pyrolysis of organosolv lignins. The goal is the conversion of lignin in fractions that can be used to replace petrochemical phenol in various applications.

8.2.2.2. Pyrolysis of pre-treated biomass. As a follow up of the BIOSYNERGY work ECN has studied the effect of various pre-treatments like torrefaction and aquathermolysis on the pyrolysis of lignocellulosic biomass. The main goal was the production of an anhydrosugar-rich bio-oil. Because of the uncertain market potential regarding the production and use of anhydrosugars, this work will end this year.

8.2.2.3. Analytical pyrolysis. Recently ECN has purchased an analytical pyrolyzer GC–MS configuration to study various samples such as lignins, lignin-oils, torrefied wood, etc.

8.2.3. Nettenergy BV

Fig. 9 Nettenergy [166] is a privately owned company which developed their own PyroFlash technology to process different biomass feedstocks into pyrolysis oil, bio-char and wood vinegar. The PyroFlash technology is based on a proprietary reactor design and a unique multi-stage separation section resulting in multiple oil fractions. The focus in developing the PyroFlash technology has been on a compact, robust design suitable for mobile installations. The activities of Nettenergy concentrate on improving the PyroFlash technology itself and analyzing its use and yield for various types of biomass (wood and residues). For the application of the pyrolysis oil three fields of research have been identified, being (i) application in diesel engines for CHP (Pyro-Engine), (ii) application in commercial burners (PyroBurn), and (iii) application in jet engines (PyroThrust).

Nettenergy BV has built a 100 kg/h installation, which will be mobile so that it can be transported to the source of the biomass. The aim is to demonstrate to the owners of biomass that conversion can be done locally and that products can also be used locally. The unit should be able to convert different types of biomass like wood and agricultural residues.

8.2.4. OPRA Turbines BV

OPRA is a gas turbine manufacturer based in Hengelo, the Netherlands. OPRA is supplier of the robust and reliable 1.8 MWe OP16 gas turbine. In 2010 OPRA performed combustion tests with pyrolysis oil supplied by BTG-BTL. Based on these tests, OPRA is modifying the combustion chambers of its gas turbine allowing 100% pyrolysis oil firing.

8.2.5. Rijksuniversiteit Groningen—RUG (Prof. Heeres)

The main activities of the chemical engineering department of the RUG involve experimental studies on the chemical and physical upgrading of pyrolysis oil with the objective to improve the product properties. The upgraded oils may find applications in the field of transportation fuels or as a co-feed for refineries, either directly or after separation into fractions by suitable separation techniques (distillation, extraction) with distinct characteristics. Some of these fractions may be enriched in added values chemicals (aromatics, phenolics, aldehydes, organic acids) and may find application as green substitutes in the current petrochemical industry [167]. Examples of upgrading technologies under study are catalytic hydrotreatment using heterogeneous catalysts and reactive blending with higher alcohols. Research activities involve upgrading studies with fast pyrolysis oil and model compounds to gain insights in reaction pathways and mechanisms, supported by extensive product characterization on both the molecular level by analytical techniques, as well as evaluation of critical product properties for the foreseen applications. The group has been involved in pyrolysis oil R&D activities both in national and international consortia (i.e., in BIOCOUP).

8.2.6. University of Twente—Energy Technology Research Group (Prof. Brem)

The Energy Technology research group of the University of Twente has several projects in the field of flash pyrolysis:

- Development of a cyclonic reactor with an integrated rotating dust filter to produce in-situ a solids-free oil vapor [168,169];
- Catalytic pyrolysis by using catalysts in the reactor for deoxygenation purposes to produce a high-value oil;
- Catalytic pyro-gasification to produce a methane-rich gas;
- Atomization of pyrolysis oil;
- Combustion of pyrolysis oil in small- and medium-scale gas turbines;

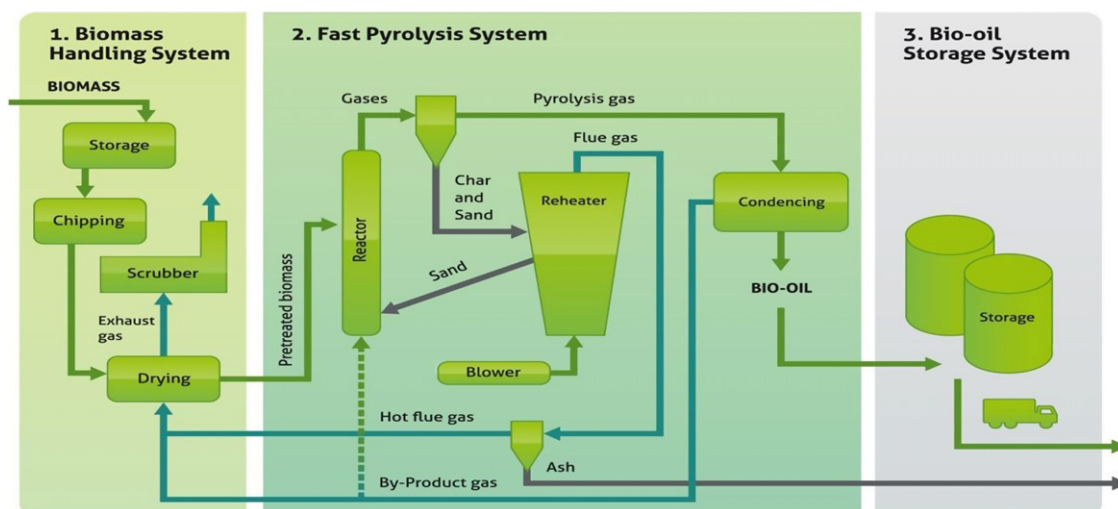


Fig. 9. Green Fuel Nordic's Biorefinery concept (© Green Fuel Nordic).

- Pyrolysis of different types of biomass and waste streams such as paper sludge, scrapped car tyres, RDF;

The laboratory of the group is well equipped with a pyrolysis pilot-plant (30 kg/h), fluidized and fixed bed reactors, a screw feed reactor, downers, a 200 kWth gas turbine, a testing facility for atomizers/nozzles, and analyzing equipment (FTIR, GCs).

8.2.7. University of Twente—Thermo-chemical conversion of biomass—TCCB (Prof. Kersten)

TCCB has been investigating fast pyrolysis since 1985. Currently, the research focuses on:

- Understanding the (initial) pyrolysis reactions. In a novel screen-heater with 10,000 °C/s heating rate and less than 20 ms hot vapor residence time, pyrolysis reactions and the effect of the feed's composition are studied.
- Fractionating while pyrolysing. A new process is worked out in which the feed is pretreated with the acid liquid from our second condenser (first condenser operating at higher temperatures). With this process liquids are obtained in the first condenser that contain more than 50% levoglucosan (yield on feed basis > 20%).
- Improving fast pyrolysis reactor technology. Step-wise pyrolysis is studied. After the first step (mild torrefaction) the biomass is ground, followed by pyrolysis at higher temperatures (+/− 500 °C).
- Pyrolyzing different types of biomass. Examples are: bagasse, EFB, straw and forest residue.
- Upgrading of pyrolysis oil to transportation fuels via mild hydrotreating. Currently, the research focuses on finding the optimal fraction of pyrolysis oil for this route.
- Upgrading of pyrolysis oil via esterification to stabilize the pyrolysis oil and reducing the acidity.
- Studying the performance of pyrolysis oils, varying in composition, in a small scale diesel engine.
- Reforming of pyrolysis oil to synthesis gas/ hydrogen. Here a hybrid system is developed that allows the add-on of a pyrolysis oil unit to a methane reformer.

The laboratory of the group is dedicated towards high-pressure research and is well equipped with a pyrolysis pilot-plant (1 kg/h), small pyrolysis units (100 g/h and 10 g/h) and fixed bed reactors with a biomass capacity between 0.01 and 1 kg. For the high pressure research, different set-ups are developed with reactor volumes between 3 and 5000 ml.

The group of Prof. Kersten is also leading the regional program “BioEnergy To Overijssel” (Be2O) with respect to the thermo-chemical processes. In Be2O projects have been defined related to the pyrolysis process itself as well as for pyrolysis oil applications.

8.2.8. Wageningen UR—Food & Biobased Research (FBR)

8.2.8.1. Pyrolysis of *Jatropha curcas* press cake. Both Wageningen and RUG are active in the field of *Jatropha* oil production and utilization. A project has been carried out on the non-food valorization of *Jatropha curcas* press cake. The majority of the work was carried out by a researcher from the Institut Teknologi Bandung (Indonesia) [170].

8.2.8.2. Use of pyrolysis oil for wood conditioning. Wageningen UR-FBR developed on lab-scale an effective formulation based on fast pyrolysis oil provided by BTG for upgrading wood properties. Treated wood showed homogeneous impregnation, improved biological durability, no leaching of harmful components and no

smell. Currently, Wageningen UR-FBR are applying for a patent on this topic. The product development will be continued in 2012 with selected partners.

8.2.8.3. Fermentation of pyrolysis oil. In cooperation with BTG and RUG a feasibility study was carried out by FBR on the microbial fermentation of the sugar fraction in pyrolysis oil. Fermentation of sugars is a well-known process, whereas the fermentation of ligno-cellulosic feedstock is currently an important issue for industrial R&D for the production of second generation biofuels. A number of micro-organisms have been tested successfully, that were able to deal with the toxic components present and also to produce biofuels. Experiments with some selected micro-organisms has led to the following conclusions: (a) Bio-oil can be added to the growth medium for up to about 25%, depending on the bio-oil pretreatment and on the micro-organism selected; (b) Bio-oil contains fermentable sugars; (c) A specific genetically modified micro-organism can use the water-soluble fraction of bio-oil as a carbon and energy source for growth; (d) In the presence of bio-oil the yeast *Saccharomyces cerevisiae* is able to convert (added) glucose into ethanol [171].

8.2.9. Other

‘CatchBio’ is a research program of 8 years in the field of catalytic biomass conversion with the aim to process the various components present in biomass in useful fuels, chemicals and pharmaceuticals [172]. Within this ‘CatchBio’ program some 10 Ph.D. projects are running at different universities on catalytic pyrolysis and related processes. This program is financed by government, industry and universities.

8.3. Demonstration activities

8.3.1. BTG Bioliquids BV

BTG BioLiquids BV (BTG-BTL) [173] is a daughter company of BTG and was established to commercialize the fast pyrolysis technology as developed by BTG. The business model is to operate as a technology supplier, supplying the core components of the pyrolysis unit.

It was determined that a demonstration unit on a commercial scale is required for proving both the technology and the complete pyrolysis chain, from biomass up to the end use of the oil. For this reason the Empyro Project (www.empyproject.eu/) was brought to life [174,175].

The main aims of the project are:

- To design, build and demonstrate a 25 MWth polygeneration pyrolysis plant to produce electricity, process steam and fuel oil from woody biomass;
- To determine the performance window of pyrolysis oil production process;
- Demonstrate the use of pyrolysis oil;
- To establish a training/education center around the demonstration plant, and set-up a Pyrolysis Platform.

The installation will be owned and operated by the company Empyro BV, a joint venture of BTG Bioliquids and Tree Power BV.

Currently (January 2012) the permitting process for the Empyro installation is almost completed. The design of the total installations has been finalized to a large extent, and the total investment cost of the installation has been determined. The plant will be built in Hengelo (NL) on the premises of AkzoNobel. The core conversion process is a flash pyrolysis process based on BTG technology. The feedstock can be either clean wood (“A-wood”) or slightly contaminated wood (“B-wood”). Excess

heat will be converted into process steam to drive a steam turbine for electricity generation. Part of the low-pressure steam will be used to dry the biomass, while excess steam will be sent to AkzoNobel.

Initially, it was foreseen that the pyrolysis oil would be co-fired in a large industrial boiler at the site of AkzoNobel. Later on, it became apparent that this was not an option for both technical and economic reasons. As a consequence, alternative users of the oil had to be found. In order to be able to convince potential customers to use pyrolysis oil, it was decided that it is essential that suppliers are able to provide guarantees on the combustion systems for pyrolysis oil. For this reason combustion tests were initiated as described in more detail below.

8.3.2. Pyrolysis oil combustion tests by Stork and Dreizler

Test programs were initiated with two burner manufacturers, Stork Technical Services (Netherlands) and Dreizler GmbH (Germany). The tests were partly funded by subsidies from the Dutch government and the province of Overijssel. For both companies, the main goal of the tests was to find out the operating window and performance of a standard oil–gas burner, firing pyrolysis oil. Using a standard burner design makes it possible to directly implement the burners at the customer's site.

The tests performed by Dreizler were done with a standard Marathon gas-oil burner on a test fire tube. Tests were done at various loads and pyrolysis oil co-firing rates. The maximum firing rate was 600 kWth, with a maximum achievable oil co-firing rate of 65%.

It was found that the burner co-firing pyrolysis oil could be operated fully automatic and in a stable way. The emissions of dust and NO_x were found to meet the limits in the Netherlands for combustion systems on biomass with a heat capacity smaller than 1 MWth. The tested burner (type) can be delivered in a range of 300 kWth up to 10 MWth.

The tests by Stork were done on the test boiler in Hengelo, a 9 MWth water tube boiler. A standard Stork Bubble Register oil and gas burner was used for the tests. Successful tests were done at a burner capacity of 2.6 MWth, with a pyrolysis oil co-firing rate of nearly 80%.

Dust and NO_x emissions were found to meet the Dutch emission limits for combustion systems firing (liquid) biomass up to a heat input of 5 MWth. Additionally, these tests have generated valuable information on the handling and combustion of wood based pyrolysis oil for heat generation. As a result, both suppliers are able to offer burner systems with performance guarantees.

8.4. Commercial activities

No full commercial projects are ongoing. The EMPYRO project is considered here as a demonstration project. However, the whole project is set-up in as a prototype commercial unit: the capacity of the plant is similar to a full commercial plant (5 t/h) and the plant should generate sufficient income to provide a positive cash flow over the next 10–15 years.

9. IEA Bioenergy Task 34

The participants in the IEA Bioenergy Task 34 for pyrolysis have also been active in the field by supporting round robins for analytical method development and in reviewing and developing standards.

Two Round Robins were undertaken in recent years. A study of lignin pyrolysis was undertaken in 2008. A refined lignin and a crude lignin were compared in fast pyrolysis systems and TGA in

the participating laboratories [32]. The similarities of crude lignin with whole biomass were identified. Refined lignin was found to be incompatible with the conventional processing conditions used in existing fluidized-bed reactors systems. A more recent Round Robin evaluated bio-oil viscosity measurement and the bio-oil accelerated aging test based on viscosity change [176]. Kinematic viscosity measurement was found to provide more consistent results compared to dynamic viscosity. Application of the aging tests was found to be highly variable and a more precisely defined and performed method is needed. The presence of suspended solids (char) in the bio-oil was found to lead to higher variability in the bio-oil measurements, generally.

Participants in the Task have also worked to establish the CAS for bio-oil (1207435-39-9) which includes a more definitive description of the product. In addition guidelines were reviewed for transportation, handling and use of bio-oil [148].

10. Conclusions

Fast pyrolysis of biomass and related processing is a rapidly advancing technology field. The six member countries of the IEA Bioenergy Task 34 on Pyrolysis are all active in the field with numerous participants in each country. Technology developers range from universities and government funded laboratories to start-up companies and well-established commercial entities. The elevated level of petroleum prices has clearly incentivized this recent development. Research is underway on numerous reactor configurations and scale-up to large demonstration units has been accomplished on a few already. Commercial implementation of fast pyrolysis for fuel oil production is on the brink of market deployment. Upgrading of the bio-oil to higher value transportation fuels is also being researched and is being scaled-up.

References

- [1] Czernik S, Bridgwater AV. Overview of applications of biomass fast pyrolysis oil. *Energy & Fuels* 2004;18:590–8.
- [2] Mohan D, Pittman CU, Steele PH. Pyrolysis of wood/biomass for bio-oil: a critical review. *Energy & Fuels* 2006;20:848–89.
- [3] Kersten SRA, Wang XQ, Prins W, van Swaaij WPM. Biomass pyrolysis in a fluidized bed reactor. Part 1: Literature review and model simulations. *Industrial & Engineering Chemistry Research* 2005;44:8773–85.
- [4] Bridgwater AV. Fast pyrolysis of biomass. In: Bridgwater AV, Hofbauer H, van Loo S, editors. *Thermal biomass conversion*. Newbury, UK: CPL Press; 2009.
- [5] Bridgwater AV. Review of fast pyrolysis of biomass and product upgrading. *Biomass and Bioenergy* 2012;38:68–94.
- [6] Bridgwater AV. Upgrading biomass fast pyrolysis liquids. In: Brown RC, editor. *Thermochemical processing of biomass: conversion into fuels, chemicals and power*. Chichester, UK: Wiley-Blackwell; 2011. p. 157–99.
- [7] Diebold JP, Milne TA, Czernik S, Oasmaa A, Bridgwater AV, Cuevas A. Proposed specifications for various grades of pyrolysis oils. In: Bridgwater AV, Boocock DGB, editors. *Thermochemical biomass conversion*. London: Blackie Academic & Professional; 1997.
- [8] Diebold JP. A review of the chemical and physical mechanisms of the storage stability of fast pyrolysis bio-oils. In: Bridgwater AV, editor. *Fast pyrolysis of biomass: a handbook*. Newbury, UK: CPL Press; 2002. p. 243–92.
- [9] <www.pyne.co.uk/?_id=120>, (accessed: 20 August, 2012).
- [10] Bridgwater AV, Maniatis K. The production of biofuels by the thermochemical processing of biomass. In: Archer MD, Barber J, editors. *Molecular to global photosynthesis*. London: IC Press; 2004. p. 521–612.
- [11] Bridgwater AV. The production of biofuels and renewable chemicals by fast pyrolysis of biomass. *International Journal of Global Energy Issues* 2007;27:160–203.
- [12] Bridgwater AV. Upgrading fast pyrolysis liquids. *Journal Environmental Progress & Sustainable Energy* 2012;31:261–8.
- [13] Scott SW, Nowakowski DJ, Bridgwater AV, Jones JM. Assess the impact of alkali metals in biomass on the physical and chemical properties of fast pyrolysis bio-oil. In: Bridgwater AV, editor. *Proceedings of the Bioten conference on biomass bioenergy and biofuels*. Newbury, UK: CPL Press; 2010.

- [14] Hodgson EM, Fahmi R, Yates N, Barraclough T, Shield I, Allison G, et al. Miscanthus as a feedstock for fast-pyrolysis: does agronomic treatment affect quality? *Bioresource Technology* 2010;101:6185–91.
- [15] Hodgson EM, Nowakowski DJ, Shield I, Riche A, Bridgwater AV, Clifton-Brown JC, et al. Variation in miscanthus chemical composition and implications for conversion by pyrolysis and thermo-chemical bio-refining for fuels and chemicals. *Bioresource Technology* 2011;102:3411–8.
- [16] Peacocke GVC, Madrali ES, Li CZ, Guell AJ, Wu F, Kandiyoti R, et al. Effect of reactor configuration on the yields and structures of pine-wood derived pyrolysis liquids—a comparison between ablative and wire-mesh pyrolysis. *Biomass & Bioenergy* 1994;7:155–67.
- [17] Papadikis K, Gu S, Bridgwater AV, Gerhauser H. Application of cfd to model fast pyrolysis of biomass. *Fuel Processing Technology* 2009;90:504–12.
- [18] Gerhauser H, Bridgwater AV. Cfd modelling of biomass pyrolysis for better fluidised bed design. In: Bridgwater AV, editor. *Proceedings of pyrolysis and gasification of biomass and waste*, strasbourg, france. Newbury, UK: CPL Scientific Press; 2003.
- [19] Gerhauser H, Generalis SC, Hague RA, Bridgwater AV. Cfd for the modelling of char entrainment in fluidised bed fast pyrolysis of biomass. In: Bridgwater AV, editor. *Progress in thermochemical biomass conversion*. Oxford, UK: Blackwell; 2001.
- [20] Papadikis K, Gu S, Bridgwater AV. Computational modelling of the impact of particle size to the heat transfer coefficient between biomass particles and a fluidised bed. *Fuel Processing Technology* 2010;91:68–79.
- [21] Papadikis K, Gu S, Bridgwater AV. Cfd modelling of the fast pyrolysis of biomass in fluidised bed reactors: modelling the impact of biomass shrinkage. *Chemical Engineering Journal* 2009;149:417–27.
- [22] Papadikis K, Gu S, Bridgwater AV. Cfd modelling of the fast pyrolysis of biomass in fluidised bed reactors. Part b heat, momentum and mass transport in bubbling fluidised beds. *Chemical Engineering Science* 2009;64:1036–45.
- [23] Papadikis K, Bridgwater AV, Gu S. Cfd modelling of the fast pyrolysis of biomass in fluidised bed reactors, part a: eulerian computation of momentum transport in bubbling fluidised beds. *Chemical Engineering Science* 2008;63:4218–27.
- [24] Sitzmann J, Bridgwater AV. Upgrading fast pyrolysis oils by hot vapour filtration. Fifteen European energy from biomass conference. Berlin 2007.
- [25] Pattiya A, Titiloye JO, Bridgwater AV. Evaluation of catalytic pyrolysis of cassava rhizome by principal component analysis. *Fuel* 2010;89:244–53.
- [26] Fahmi R, Bridgwater AV, Thain SC, Donnison IS, Morris PM, Yates N. Prediction of klason lignin and lignin thermal degradation products by py-gc/ms in a collection of lolium and festuca grasses. *Journal of Analytical and Applied Pyrolysis* 2007;80:16–23.
- [27] Greenhalf CE, Nowakowski DJ, Bridgwater AV, Titiloye J, Yates N, Riche A, et al. Thermochemical characterisation of straws and high yielding perennial grasses. *Industrial Crops and Products* 2012;36:449–59.
- [28] Harms AB, Nowakowski DJ, Bridgwater AV. Fast pyrolysis processing of agricultural and forestry residue: nitrogen recycling and carbon sequestration. In: Bridgwater AV, editor. *Proceedings of the Bioten conference on biomass bioenergy and biofuels*. Newbury, UK: CPL Press; 2010.
- [29] Pattiya A, Titiloye JO, Bridgwater AV. Fast pyrolysis of cassava rhizome in the presence of catalysts. *Journal of Analytical and Applied Pyrolysis* 2008;81:72–9.
- [30] Jiang GZ, Nowakowski DJ, Bridgwater AV. Effect of the temperature on the composition of lignin pyrolysis products. *Energy & Fuels* 2010;24:4470–5.
- [31] Jiang GZ, Nowakowski DJ, Bridgwater AV. A systematic study of the kinetics of lignin pyrolysis. *Thermochimica Acta* 2010;498:61–6.
- [32] Nowakowski DJ, Bridgwater AV, Elliott DC, Meier D, de Wild P. Lignin fast pyrolysis: results from an international collaboration. *Journal of Analytical and Applied Pyrolysis* 2010;88:53–72.
- [33] Effendi A, Gerhauser H, Bridgwater AV. Production of renewable phenolic resins by thermochemical conversion of biomass: a review. *Renewable & Sustainable Energy Reviews* 2008;12:2092–116.
- [34] Bridgwater AV, Toft AJ, Brammer JG. A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. *Renewable & Sustainable Energy Reviews* 2002;6:181–248.
- [35] Peacocke GVC, Bridgwater AV. Techno-economic assessment of power production from the wellman process engineering and btg fast pyrolysis processes. In: Bridgwater AV, Boocock DGB, editors. *Science in thermal and chemical conversion*. Newbury, UK: CPL Press; 2004. p. 1785–802.
- [36] Alexander S, Brammer JG, Bridgwater AV. Technical assessment of ammonia production via biomass gasification. In: Bridgwater AV, editor. *Proceedings of the Bioten conference on biomass bioenergy and biofuels*. Newbury, UK: CPL Press; 2011.
- [37] Chong KJ, Bridgwater AV. A methodology to generate, analyse and compare biorefinery process chains. In: Bridgwater AV, editor. *Proceedings of the Bioten conference on biomass bioenergy and biofuels*: CPL Press; 2011. p. 229–443.
- [38] Dimitriou I, Bridgwater AV, Pröll T. Process analysis of large-scale biomass-to-liquids (btl) plants based on gasification. *Proceedings of ICPS1*. Vienna, Austria: TUV Vienna; 2011.
- [39] Darvell LI, Jones JM, Gudka B, Baxter XC, Saddawi A, Williams A, et al. Combustion properties of some power station biomass fuels. *Fuel* 2010;89:2881–90.
- [40] Jones JM, Williams A, Darvell LI, Nawaz M, Baxter X. The role of metals in biomass pyrolysis, char formation and char properties. In: Bridgwater AV, Boocock DGB, editors. *Science in thermal and chemical biomass conversion*. Newbury, UK: CPL Press; 2006. p. 1203–14 cpl press uk 2006.
- [41] Ross AB, Hanley I, Dupont V, Jones JM, Twigg MV. Demonstration of unmixed steam reforming of vegetable oil. In: Bridgwater AV, Boocock, editors. *Science in thermal and chemical biomass conversion*. Newbury, UK: CPL Press; 2006. p. 444–59.
- [42] Bryan PF. Biomass program overview presentation at the biomass program peer review, June 27. Washington, D.C.2011.
- [43] <obpview2011.govtools.us/thermochem/>, (accessed: 20 August, 2012).
- [44] Javaid A, Ryan T, Berg G, Pan XM, Vispute T, Bhatia SR, et al. Removal of char particles from fast pyrolysis bio-oil by microfiltration. *Journal of Membrane Science* 2010;363:120–7.
- [45] Vispute TP, Zhang HY, Sanna A, Xiao R, Huber GW. Renewable chemical commodity feedstocks from integrated catalytic processing of pyrolysis oils. *Science* 2010;330:1222–7.
- [46] <www.obpview2011.govtools.us>, (accessed: 20 August, 2012).
- [47] Pavani M, Sharma P, Cooper M, Dayton DC, Gupta R, Noch zu korrigieren.
- [48] Agblevor FA, Mante O, Abdoulmoumine N, McClung R. Production of stable biomass pyrolysis oils using fractional catalytic pyrolysis. *Energy & Fuels* 2010;24:4087–9.
- [49] Agblevor FA, Shao J. New method of total acid number (tan) determination in biooils. *American Institute of Chemical Engineers* 2010 p. a571/a-3.
- [50] Zhao HY, Li D, Bui P, Oyama ST. Hydrodeoxygenation of guaiacol as model compound for pyrolysis oil on transition metal phosphide hydroprocessing catalysts. *Appl Catal A-Gen* 2011;391:305–10.
- [51] <obpview2011.govtools.us>, (accessed: 20 August, 2012).
- [52] Mei DH, Karim AM, Wang Y. Density functional theory study of acetaldehyde hydrodeoxygenation on moo3. *Journal of Physical Chemistry C* 2011;115:8155–64.
- [53] <www.nabcpjournals.org>, (accessed: 20 August, 2012).
- [54] French R, Czernik S. Catalytic pyrolysis of biomass for biofuels production. *Fuel Processing Technology* 2010;91:25–32.
- [55] Moens L, Black SK, Myers MD, Czernik S. Study of the neutralization and stabilization of a mixed hardwood bio-oil. *Energy & Fuels* 2009;23:2695–9.
- [56] Jones SB, Valkenburg C, Walton C, Elliott DC, Holladay JE, Stevens DJ, et al. Production of gasoline and diesel from biomass via fast pyrolysis, hydrotreating and hydrocracking: a design case. US Department of Energy 2009;76.
- [57] Arbogast SV. Preferred paths for commercializing pyrolysis oil at conventional refineries, deliverable 1, quality considerations for the transport and processing of pyrolysis oil in existing petroleum refineries. Houston, TX: Global Energy Management Institute; 2008.
- [58] French RJ, Hrdlicka J, Baldwin R. Mild hydrotreating of biomass pyrolysis oils to produce a suitable refinery feedstock. *Environmental Progress & Sustainable Energy* 2010;29:142–50.
- [59] French RJ, Stunkel J, Baldwin RM. Mild hydrotreating of bio-oil: effect of reaction severity and fate of oxygenated species. *Energy & Fuels* 2011;25:3266–74.
- [60] Elliott DC, Hart TR. Catalytic hydroprocessing of chemical models for bio-oil. *Energy & Fuels* 2009;23:631–7.
- [61] Elliott DC, Hu J, Hart TR, Neuenschwander GG. Palladium catalyzed hydrogenation of bio-oils and organic compounds. US: Battelle Memorial Institute, Richland, WA; 2007 06062007.
- [62] Elliott DC, Hu J, Hart TR, Neuenschwander GG. Palladium catalyzed hydrogenation of bio-oils and organic compounds. US: Battelle Memorial Institute, Richland, WA; 2011 07062011.
- [63] Elliott DC, Hart TR, Neuenschwander GG, Rotness LJ, Zacher AH. Catalytic hydroprocessing of biomass fast pyrolysis bio-oil to produce hydrocarbon products. *Environmental Progress & Sustainable Energy* 2009;28:441–9.
- [64] Oasmaa A, Elliott DC, Korhonen J. Acidity of biomass fast pyrolysis bio-oils. *Energy & Fuels* 2010;24:6548–54.
- [65] Oasmaa A, Elliott DC, Müller S. Quality control in fast pyrolysis bio-oil production and use. *Environmental Progress & Sustainable Energy* 2009;28:404–9.
- [66] Mullen CA, Boateng AA. Chemical composition of bio-oils produced by fast pyrolysis of two energy crops. *Energy & Fuels* 2008;22:2104–9.
- [67] Boateng AA, Mullen CA, Goldberg NM, Hicks KB, McMahan CM, Whalen MC, et al. Energy-dense liquid fuel intermediates by pyrolysis of guayule (*Parthenium argentatum*) shrub and bagasse. *Fuel* 2009;88:2207–15.
- [68] Mullen CA, Boateng AA, Goldberg NM, Lima IM, Laird DA, Hicks KB. Bio-oil and bio-char production from corn cobs and stover by fast pyrolysis. *Biomass & Bioenergy* 2010;34:67–74.
- [69] Mullen CA, Boateng AA, Hicks KB, Goldberg NM, Moreau RA. Analysis and comparison of bio-oil produced by fast pyrolysis from three barley biomass/byproduct streams. *Energy & Fuels* 2010;24:699–706.
- [70] Boateng AA, Mullen CA, Goldberg NM. Producing stable pyrolysis liquids from the oil-seed presscakes of mustard family plants: pennycress (*Thlaspi arvense* L.) and camelina (*Camelina sativa*). *Energy & Fuels* 2010;24:6624–32.
- [71] Compton DL, Jackson MA, Mihalcik DJ, Mullen CA, Boateng AA. Catalytic pyrolysis of oak via pyroprobe and bench scale, packed bed pyrolysis reactors. *Journal of Analytical and Applied Pyrolysis* 2011;90:174–81.
- [72] Mullen CA, Boateng AA. Catalytic pyrolysis-gc/ms of lignin from several sources. *Fuel Processing Technology* 2010;91:1446–58.
- [73] Mullen CA, Strahan GD, Boateng AA. Characterization of various fast-pyrolysis bio-oils by nmr spectroscopy. *Energy & Fuels* 2009;23:2707–18.

- [74] Mullen CA, Boateng AA. Characterization of water insoluble solids isolated from various biomass fast pyrolysis oils. *Journal of Analytical and Applied Pyrolysis* 2011;90:197–203.
- [75] Wright MM, Daugaard DE, Satrio JA, Brown RC. Techno-economic analysis of biomass fast pyrolysis to transportation fuels. *Fuel* 2010;89:511–9.
- [76] Ortiz-Toral PJ, Satrio J, Brown RC, Shanks BH. Steam reforming of bio-oil fractions: effect of composition and stability. *Energy & Fuels* 2011;25:3289–97.
- [77] DeSisto WJ, Hill N, Beis SH, Mukkamala S, Joseph J, Baker C, et al. Fast pyrolysis of pine sawdust in a fluidized-bed reactor. *Energy & Fuels* 2010;24:2642–51.
- [78] Joseph J, Baker C, Mukkamala S, Beis SH, Wheeler MC, DeSisto WJ, et al. Chemical shifts and lifetimes for nuclear magnetic resonance (nmr) analysis of biofuels. *Energy & Fuels* 2010;24:5153–62.
- [79] Garcia-Perez M, Wang XS, Shen J, Rhodes MJ, Tian FJ, Lee WJ, et al. Fast pyrolysis of oil mallee woody biomass: effect of temperature on the yield and quality of pyrolysis products. *Industrial & Engineering Chemistry Research* 2008;47:1846–54.
- [80] Garcia-Perez M, Wang S, Shen J, Rhodes M, Lee WJ, Li CZ. Effects of temperature on the formation of lignin-derived oligomers during the fast pyrolysis of mallee woody biomass. *Energy & Fuels* 2008;22:2022–32.
- [81] Mourant D, Wang ZH, He M, Wang XS, Garcia-Perez M, Ling KC, et al. Mallee wood fast pyrolysis: effects of alkali and alkaline earth metallic species on the yield and composition of bio-oil. *Fuel* 2011;90:2915–22.
- [82] Li X, Gunawan R, Lievens C, Wang Y, Mourant D, Wang S, et al. Simultaneous catalytic esterification of carboxylic acids and acetalisation of aldehydes in a fast pyrolysis bio-oil from mallee biomass. *Fuel* 2011;90:2530–7.
- [83] Lian JN, Chen SL, Zhou SA, Wang ZH, O'Fallon J, Li CZ, et al. Separation, hydrolysis and fermentation of pyrolytic sugars to produce ethanol and lipids. *Bioresource Technology* 2010;101:9688–99.
- [84] Garcia-Perez M, Shen J, Wang XS, Li CZ. Production and fuel properties of fast pyrolysis oil/bio-diesel blends. *Fuel Processing Technology* 2010;91:296–305.
- [85] Westerhof RJM, Brilman DWF, Garcia-Perez M, Wang Z, Oudenhoven SRG, van Swaaij WPM, et al. Fractional condensation of biomass pyrolysis vapors. *Energy & Fuels* 2011;25:1817–29.
- [86] Johnson RL, Liaw SS, Garcia-Perez M, Ha S, Lin SSY, McDonald AG, et al. Pyrolysis gas chromatography mass spectrometry studies to evaluate high-temperature aqueous pretreatment as a way to modify the composition of bio-oil from fast pyrolysis of wheat straw. *Energy & Fuels* 2009;23:6242–52.
- [87] Lei HW, Ren SJ, Wang L, Bu Q, Julson J, Holladay J, et al. Microwave pyrolysis of distillers dried grain with solubles (ddgs) for biofuel production. *Bioresource Technology* 2011;102:6208–13.
- [88] Bu Q, Lei HW, Ren SJ, Wang L, Holladay J, Zhang Q, et al. Phenol and phenolics from lignocellulosic biomass by catalytic microwave pyrolysis. *Bioresource Technology* 2011;102:7004–7.
- [89] Lei HW, Ren SJ, Julson J. The effects of reaction temperature and time and particle size of corn stover on microwave pyrolysis. *Energy & Fuels* 2009;23:3254–61.
- [90] Wan YQ, Chen P, Zhang B, Yang CY, Liu YH, Lin XY, et al. Microwave-assisted pyrolysis of biomass: catalysts to improve product selectivity. *Journal of Analytical and Applied Pyrolysis* 2009;86:161–7.
- [91] Du ZY, Li YC, Wang XQ, Wan YQ, Chen Q, Wang CG, et al. Microwave-assisted pyrolysis of microalgae for biofuel production. *Bioresource Technology* 2011;102:4890–6.
- [92] Ingram L, Mohan D, Bricka M, Steele P, Strobel D, Crocker D, et al. Pyrolysis of wood and bark in an auger reactor: physical properties and chemical analysis of the produced bio-oils. *Energy & Fuels* 2008;22:614–25.
- [93] Hassan EBM, Steele PH, Ingram L. Characterization of fast pyrolysis bio-oils produced from pretreated pine wood. *Applied Biochemistry and Biotechnology* 2009;154:182–92.
- [94] Bhattacharya P, Steele PH, Hassan EBM, Mitchell B, Ingram L, Pittman CU. Wood/plastic copyrolysis in an auger reactor: chemical and physical analysis of the products. *Fuel* 2009;88:1251–60.
- [95] Tripathi MM, Hassan EM, Yueh FY, Singh JP, Steele PH. Study of the effect of ultraviolet exposure on bio-oil by laser-induced fluorescence spectroscopy. *Energy & Fuels* 2010;24:6187–92.
- [96] Nolte MW, Liberatore MW. Viscosity of biomass pyrolysis oils from various feedstocks. *Energy & Fuels* 2010;24:6601–8.
- [97] Holmgren J, Marinangeli R, Nair P, Elliott DC, Bain R. Consider upgrading pyrolysis oils into renewable fuels. *Hydrocarbon Processing* 2008;87:95–6, 8, 100, 3.
- [98] Marker TL, Felix LG, Linck MB, Roberts MJ. Integrated hydrolysis and hydroconversion (ih2) for the direct production of gasoline and diesel fuels or blending components from biomass, part 1: proof of principle testing. *Environmental Progress & Sustainable Energy* 2012;31:191–9.
- [99] <www.fpac.ca/index.php/en/bio-pathways/>, (accessed: 20 August, 2012).
- [100] <cfs.nrcan.gc.ca/pages/232?lang=en_CA>, (accessed: 20 August, 2012).
- [101] <www.cribe.ca/projects/content/projects/article/domtar>, (accessed: 20 August, 2012).
- [102] Berruti F, Briens C, Ferrante L. A mobile pyrolysis technology for the conversion of biomass into bio-oil. Eighth world congress of chemical engineering conference and the 24th interamerican congress of chemical engineering 2009.
- [103] <www.ensyn.com/>, (accessed: 20 August, 2012).
- [104] <www.envergenttech.com/>, (accessed: 20 August, 2012).
- [105] <www.astm.org/Standards/D7544.htm>, (accessed: 20 August, 2012).
- [106] Scott DS, Piskorz J. Continuous flash pyrolysis of wood for production of liquid fuels. *Energy Biomass Wastes* 1983;7:1123–46.
- [107] Brown RC, Radlein D, Piskorz J. Pretreatment processes to increase pyrolytic yield of levoglucosan from herbaceous feedstocks. In: Bozell JJ, editor. *Chemicals and materials from renewable resources*. Washington, DC 2001. p. 123–132.
- [108] Piskorz J, Majerski P, Radlein D, Scott DS, Bridgwater AV. Fast pyrolysis of sweet sorghum and sweet sorghum bagasse. *Journal of Analytical and Applied Pyrolysis* 1998;46:15–29.
- [109] Piskorz J, Majerski P, Radlein D, Vladars-Usas A, Scott DS. Flash pyrolysis of cellulose for production of anhydro-oligomers. *Journal of Analytical and Applied Pyrolysis* 2000;56:145–66.
- [110] Preto F, Gogolek PEG, JKL W. Nozzle testing and development for bio-oil combustion. *Science in Thermal and Chemical Biomass Conversion*. Victoria, Canada September 2004.
- [111] Preto F. Biomass pyrolysis oils: a future fuel? Oil Heat 2005 Halifax: Canadian: Oil Heat Association; 2005 May.
- [112] Preto F, Zhang F, Hogan E. Biomass pyrolysis oil utilization by co-firing with natural gas in lumber drying kilns. Fourteen European conference and exhibition on biomass for energy, industry and climate protection. Paris October 2005.
- [113] Preto F, Coyle I, Wong JKL, Zhang F. Combustion of pyrolysis 'bio-oils' in a tunnel furnace. *Bioenergy—II: fuels and chemicals from renewable resources*. Rio de Janeiro, Brazil March 2009.
- [114] Schnitzer MI, Monreal CM, Facey GA, Fransham PB. The conversion of chicken manure to biooil by fast pyrolysis i. Analyses of chicken manure, biooils and char by c-13 and h-1 nmr and ftr spectrophotometry. *Journal of Environmental Science and Health, Part B Pesticides* 2007;42:71–7.
- [115] Schnitzer MI, Monreal CM, Jandl G, Leinweber P, Fransham PB. The conversion of chicken manure to biooil by fast pyrolysis ii. Analysis of chicken manure, biooils, and char by curie-point pyrolysis-gas chromatography/mass spectrometry (cp py-gc/ms). *Journal of Environmental Science and Health, Part B Pesticides* 2007;42:79–95.
- [116] Preto F, Hogan E A. Pyrolysis based biorefinery approach. Fourteen European conference and exhibition on biomass for energy, industry and climate protection. Paris October 2005.
- [117] Sobhy A, Chaoki J. Microwave-assisted biorefinery. *Chemical Engineering Transactions* 2010;19:25–9.
- [118] Tzanetakis T, Ashgriz N, James DF, Thomson MJ. Liquid fuel properties of a hardwood-derived bio-oil fraction. *Energy & Fuels* 2008;22:2725–33.
- [119] Tzanetakis T, Farra N, Moloodi S, Lamont W, McGrath A, Thomson MJ. Spray combustion characteristics and gaseous emissions of a wood derived fast pyrolysis liquid-ethanol blend in a pilot stabilized swirl burner. *Energy & Fuels* 2010;24:5331–48.
- [120] Tzanetakis T, Moloodi S, Farra N, Nguyen B, Thomson MJ. Spray combustion and particulate matter emissions of a wood derived fast pyrolysis liquid-ethanol blend in a pilot stabilized swirl burner. *Energy & Fuels* 2011;25:1405–22.
- [121] Khan U, Tzanetakis T, Thomson MJ, Kim S. Efficiency and emissions study of a residential micro-cogeneration system based on a modified stirling engine and fuelled by a wood derived fast pyrolysis liquid-ethanol blend. *Combustion Institute Canadian Section Spring Technical Meeting*. Toronto, Canada 2012.
- [122] <www.icfar.ca/>, (accessed: 20 August, 2012).
- [123] Karimi E, Briens C, Berruti F, Moloodi S, Tzanetakis T, Thomson MJ, et al. Red mud as a catalyst for the upgrading of hemp-seed pyrolysis bio-oil. *Energy & Fuels* 2010;24:6586–600.
- [124] Berruti FM, Ferrante L, Briens CL, Berruti F. Pyrolysis of cohesive meat and bone meal in a bubbling fluidized bed with an intermittent solid slug feeder. *Journal of Analytical and Applied Pyrolysis* 2012;94:153–62.
- [125] Palmisano P, Berruti F, Briens C. Effect of biochar on product yield and quality during pyrolysis of biomass in a bubbling fluidized bed reactor. In: 19th international symposium on analytical and applied pyrolysis. Linz, Austria May 2012.
- [126] <www.sdtc.ca/uploads/documents/en/2004_ar_supplimental.Pdf>, (accessed: 20 August, 2012).
- [127] <www.hydro.mb.ca/>, (accessed: 20 August, 2012).
- [128] Roy C. Personal communication. 2012.
- [129] Wagenaar BM, Venderbosch RH, Carrasco J, Strenziok R, Aa Bjvd. Rotating cone bio-oil production and application. In: Bridgwater AV, editor. *Progress in thermochemical biomass conversion*. Oxford: Blackwell Science; 2001. p. 1268–80.
- [130] Hansen U, Strenziok R, Wagenaar BM, Meier D. Energetic utilization of contaminated wood waste of flash pyrolysis. Dgmk tagungsberichte. Hamburg: Deutsche Wissenschaftliche Gesellschaft fuer Erdoel, Erdgas und Kohle; 2002 p. 341–347.
- [131] Hansen U, Strenziok R, Wendig D, Kautz M. Biogenic fuels in the small gas turbine. *VDI-Ber* 2003;1746:119–34.
- [132] Faix O, Fortmann L, Bremer J, Meier D. Thermal degradation products of wood. A collection of electron-impact (ei) mass spectra of polysaccharide-derived products. *Holz als Roh- und Werkstoff* 1991;49:299–304.
- [133] Faix O, Meier D, Fortmann I. Thermal degradation products of wood. Gas chromatographic separation and mass spectrometric characterization of

- monomeric lignin-derived products. *Holz als Roh- und Werkstoff* 1990;48: 281–9.
- [134] Faix O, Meier D, Fortmann I. Thermal degradation products of wood: a collection of electron-impact (ei) mass spectra of monomeric lignin derived products. *Holz als Roh- und Werkstoff* 1990;48:351–4.
- [135] Faix O, Fortmann I, Bremer J, Meier D. Thermal degradation products of wood. Gas chromatographic separation and mass spectrometric characterization of polysaccharide derived products. *Holz als Roh- und Werkstoff* 1991;49:213–9.
- [136] Windt M, Meier D, Marsman JH, Heeres HJ, de Koning S. Micro-pyrolysis of technical lignins in a new modular rig and product analysis by GC–MS/MS and GCxGC–TOFMS/MS. *Journal of Analytical and Applied Pyrolysis* 2009;85: 38–46.
- [137] Azeez AM, Meier D, Odermatt J. Temperature dependence of fast pyrolysis volatile products from European and African biomasses. *Journal of Analytical and Applied Pyrolysis* 2011;90:81–92.
- [138] Gerdes C, Simon CM, Ollesch T, Meier D, Kaminsky W. Design, construction, and operation of a fast pyrolysis plant for biomass. *Engineering in Life Sciences* 2002;2:167–74.
- [139] Armbruster U. Heterogeneously catalysed deoxygenation of pyrolysis oil in hot compressed water to produce fuel components. *PyNE Newsletter* 2011;30:36–7.
- [140] Meier D, Schöll S, Klaubert H, Markgraf J. Practical results from pytec's biomass-to-oil (bto) process with ablative pyrolyser and diesel chp plant. In: Bridgwater AV, editor. *BioE—success and visions for bioenergy*. CPL Scientific Publishing Service Ltd; 2007.
- [141] Faix A, Schweinle J, Schöll S, Becker G, Meier D. (gti-tcbiomass) life-cycle assessment of the btoE-process (biomass-to-oil) with combined heat and power generation. *Environmental Progress & Sustainable Energy* 2010;29: 193–202.
- [142] Oasmaa A, Solantausta Y, Arpiainen V, Kuoppala E, Sipilä K. Fast pyrolysis bio-oils from wood and agricultural residues. *Energy & Fuels* 2010;24:1380–8.
- [143] <www.metso.com/news/newsdocuments.nsf/Web3NewsDoc/4AA4186AD7B97A4AC225767E00305FBF?OpenDocument&ch=ChMetsoEnergyWeb&id=4AA4186AD7B97A4AC225767E00305FBF& >, (accessed: 20 August, 2012).
- [144] Lehto J, Jokela P, Alin J, Solantausta Y, Oasmaa A. Bio-oil production integrated with a fluidized bed boiler—experiences from a pilot project. In: *Engineering PP*, editor.: PennWell; 2010. p. 182–187.
- [145] Solantausta Y, Oasmaa A, Sipilä K, Lindfors C, Lehto J, Autio J, et al. Bio-oil production from biomass: steps toward demonstration. *Energy & Fuels* 2012;26:233–40.
- [146] Lehto J, Jokela P, Oasmaa A, Solantausta Y. Integrated heat, electricity and bio-oil production. *Biofuels Innovator* 2010:20–2.
- [147] Oasmaa A, Peacocke C. Properties and fuel use of biomass derived fast pyrolysis liquids—a guide. Espoo: VTT; 2010.
- [148] Oasmaa A, Kalli A, Lindfors C, Elliott DC, Springer D, Peacocke C, et al. Guidelines for transportation, handling, and use of fast pyrolysis bio-oil. 1. Flammability and toxicity. *Energy & Fuels* 2012;26:3864–73.
- [149] Oasmaa A, Kuoppala E, Solantausta Y. Fast pyrolysis of forestry residue. 2. Physicochemical composition of product liquid. *Energy & Fuels* 2003;17: 433–43.
- [150] Oasmaa A, Kuoppala E. Solvent fractionation method with brix for rapid characterization of wood fast pyrolysis liquids. *Energy & Fuels* 2008;22: 4245–8.
- [151] Oasmaa A, Kuoppala E. Fast pyrolysis of forestry residue. 3. Storage stability of liquid fuel. *Energy & Fuels* 2003;17:1075–84.
- [152] Oasmaa A, Korhonen J, Kuoppala E. An approach for stability measurement of wood-based fast pyrolysis bio-oils. *Energy & Fuels* 2011;25:3307–13.
- [153] Oasmaa A, Kuoppala E, Selin JF, Gust S, Solantausta Y. Fast pyrolysis of forestry residue and pine. 4. Improvement of the product quality by solvent addition. *Energy & Fuels* 2004;18:1578–83.
- [154] Oasmaa A, Sipilä K, Solantausta Y, Kuoppala E. Quality improvement of pyrolysis liquid: effect of light volatiles on the stability of pyrolysis liquids. *Energy & Fuels* 2005;19:2556–61.
- [155] Aho A, Kumar N, Lashkul AV, Eränen K, Ziolek M, Decyk P, et al. Catalytic upgrading of woody biomass derived pyrolysis vapours over iron modified zeolites in a dual-fluidized bed reactor. *Fuel* 2010;89:1992–2000.
- [156] Sipilä K. Research into thermochemical conversion of biomass into fuels, chemicals and fibers. *Biomass Energy Environ. Agric. Ind. In Proc. Eur. Biomass Conf. 8th (1995) Meeting Date 1994 Volume 1* 156–67. Editor(s): Chatter Philippe; Beenackers A. A. C. M.; Grassi G. Publisher: Elsevier Oxford UK. CODEN: 62MKAA.
- [157] Pöyry. Market potential of bio-oil production in north American forest industry. *Pyöry Management Consulting Oy*; 2010.
- [158] <www.biocoup.com/index.php?id=18>, (accessed: 20 August, 2012).
- [159] <www.teknikkatalous.fi/energia/green+fuel+nordic+rakentaa+kolme+biojalostamo+suomeen/a702627>, (accessed: 20 August, 2012).
- [160] *Hernieuwbare energie in Nederland 2010*, Centraal Bureau voor de Statistiek. 2010.
- [161] <www.btgworld.com>, (accessed: 20 August, 2012).
- [162] Van de Beld L, Holle E, Florijn J. An experimental study on the use of pyrolysis oil in diesel engines for chp applications. 19th European Biomass conference and exhibition 2011. 1181–1187.
- [163] <www.suprabio.eu>, (accessed: 20 August, 2012).
- [164] Venderbosch RH, Ardiyanti AR, Wildschut J, Oasmaa A, Heeres HJ. Stabilization of biomass-derived pyrolysis oils. *Journal of Chemical Technology and Biotechnology* 2010;85:674–86.
- [165] Wildschut J, Mahfud FH, Venderbosch RH, Heeres HJ. Hydrotreatment of fast pyrolysis oil using heterogeneous noble-metal catalysts. *Industrial & Engineering Chemistry Research* 2009;48:10324–34.
- [166] <www.nettenergy.com>, (accessed: 20 August, 2012).
- [167] Rasrendra CB, Girisuta B, van de Bovenkamp HH, Winkelman JGM, Leijenhorst EJ, Venderbosch RH, et al. Recovery of acetic acid from an aqueous pyrolysis oil phase by reactive extraction using tri-n-octylamine. *Chemical Engineering Journal* 2011;176–177:244–52.
- [168] Bramer EA, Brem G. A new technology for fast pyrolysis of biomass, development of the pyros reactor. Pyrolysis and gasification of biomass and waste, proceedings of an expert meeting. Strasbourg, France: CPL Press; 2002. p. 63–73.
- [169] Bramer EA, Brem G. The pyros reactor: a cyclonic flash pyrolysis reactor with internal particle filter. In: Bridgwater AV, editor. *Proc of the bioten conference on biomass bioenergy and biofuels 2010*. Newbury: CPL Press; 2011. p. 447–58.
- [170] Manurung R, Weuer DAZ, Wildschut J, Venderbosch RH, Hidayat H, van Dam JEG, et al. Valorisation of *Jatropha curcas* L. Plant parts: nut shell conversion to fast pyrolysis oil. *Food and Bioproducts Processing* 2009;87:187–96.
- [171] Mooibroek H, van Dam JEG, Springer J, Leijenhorst EJ, Venderbosch RH, Heeres HJ. Fermentation of bio-oil. In: *study Oof*, editor.: *Energie Onderzoek Subsidie: Nieuw Energieonderzoek*; 2010.
- [172] <www.CatchBio.com>, (accessed: 20 August, 2012).
- [173] <www.btg-btl.com>, (accessed: 20 August, 2012).
- [174] <www.empyropoject.eu/>, (accessed: 20 August, 2012).
- [175] <www.mpi-group.net/>, (accessed: 20 August, 2012).
- [176] Elliott DC, Oasmaa A, Preto F, Meier D, Bridgwater AV. Results of the IEA round robin on viscosity and stability of fast pyrolysis bio-oils. *Energy & Fuels* 2012;26:3769–76.